

EVALUATION OF CRITERIA
FOR IMPROVED DURABILITY OF ASPHALT

By

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Abstract of Dissertation Presented to the Graduate School
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EVALUATION OF CRITERIA
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A research study was conducted to evaluate the feasibility of establishing suitable criteria to ensure improved durability of asphalt. Twenty representative asphalts commonly used in Florida and its neighboring states were selected and used in a laboratory testing program to evaluate their aging characteristics. For each of the asphalts, tests were performed on the asphalts and the asphalt residues after the thin film oven test and rolling thin film oven test at 285, 325, and 365 °F.

Of the twenty asphalts evaluated in the asphalt binder test, five asphalts were used in a laboratory testing program to establish relationships between mixture properties and the binder properties. Each of these five asphalts was used to make Florida S-1 asphalt concrete mixtures, and Marshall specimens were fabricated from these mixtures. The compacted Marshall specimens were subjected to different aging conditions, i.e., aging in convectional oven at 140 °F, aging in

forced draft oven at 140 °F, aging in ultraviolet oven at 140 °F, and aging under natural sunlight for different periods of time.

Indirect tensile, resilient modulus, and fracture energy tests were performed on all Marshall specimens at two levels of temperature. Asphalt residues were recovered from the broken samples and subjected to consistency tests. Schweyer rheometer tests were conducted at two temperatures for evaluation of aging effects. Also, core samples and recovered asphalt residues from two paving projects at various ages were evaluated for consistency and infrared spectral characteristics.

Analyses of variance and regression analyses were performed on the results to determine the significance of test parameters and to establish relationships. The effects of different artificial aging processes were compared. Relationships between laboratory aging and field aging were established. Infrared spectroscopic techniques were used effectively to identify the aging effects of asphalt binders. The Schweyer rheometer test can be used to directly measure the cracking potential of asphalt mixture at low temperature. An improved specification for durability of asphalt binders is recommended.

CHAPTER 1 INTRODUCTION

1.1 Background

It has been recognized that the properties of the asphalt binders play a major role in the performance of asphalt concrete pavements. In the last fifty years, there has been a steady increase in the research on the properties of highway asphalts for the development of improved specifications to ensure that good asphalts could be used in highway construction. It is important that the selected asphalt for paving not only have the desirable properties at the time of placement but also have good long term performance.

Current asphalt binder specifications are not sufficient to ensure good long term performance. The thin film oven test (TFOT) or rolling thin film test (RTFOT), adopted by almost all the highway agencies, can only estimate the property changes of asphalt binders during the hot mixing process. There is not adequate information on change in properties during service in the pavement. Also, current asphalt binder specifications lack tests at low temperature. The properties of asphalt binders at low temperature are extrapolated from those at high temperature. This practice results in confusion and inaccuracy.

Therefore, it is necessary to have tests which can be used to predict the properties of the asphalt binder during service in the pavement, and tests which can be used to measure the properties of asphalt binders at low temperature directly.

In a recent research done at the University of Florida [1], an investigation was conducted on the age hardening trends of typical asphalt binders in laboratory controlled aging environments and in actual paving projects. From the results of the research, certain test methods and criteria were developed for selection of asphalt for good long term performance. The recommended test methods and criteria are as follows:

1. Infrared spectral analyses are recommended to be performed on the original asphalt and the artificially aged asphalt residue. The analysis result may be used as a criterion for selection of asphalt for long term durability.
2. Schwyer rheometer tests are recommended to be performed on the aged asphalt residue to determine its constant power viscosity at low temperature (41° F). The low temperature viscosity of the aged asphalt is a more direct measure of the cracking potential of the asphalt mixture at low temperature, as compared with using a high temperature viscosity (such as absolute viscosity at 140° F) for prediction of low temperature cracking. The low temperature constant power viscosity may be used as a criterion to reduce low temperature cracking.

However, the recommended test methods and criteria are based on results of tests on a limited number of asphalts. A more extensive evaluation of these proposed criteria is needed to establish their validity and suitable values for these criteria to be used for selection of asphalts.

1.2 Study Objectives

The main objectives of this study are as follows:

1. To evaluate the criteria for selection of asphalt using infrared spectral analysis technique, artificial aging processes and low temperature Schweyer rheometer tests.
2. To modify the proposed testing procedures so that they could be used conveniently and effectively by highway agencies.
3. To establish relationships between field and laboratory aged samples.

1.3 Research Program

The work in this research program is divided into the following subtasks:

- (1) Testing program on asphalt binders to evaluate aging characteristics
- (2) Testing program on asphalt mixtures to establish relationship between binder and mixture properties
- (3) Sampling and testing of cores from paving projects
- (4) Continuation of previous study on natural aging of asphalt mixtures.

The subtasks of the research program and their interrelationships are shown in Figure 1.1. This section presents the testing program in each of these subtasks in details.

1.3.1 Testing Program on Asphalt Binders

Twenty representative asphalts commonly used in Florida and its neighboring states were selected to be used in a laboratory testing

RESEARCH PROJECT

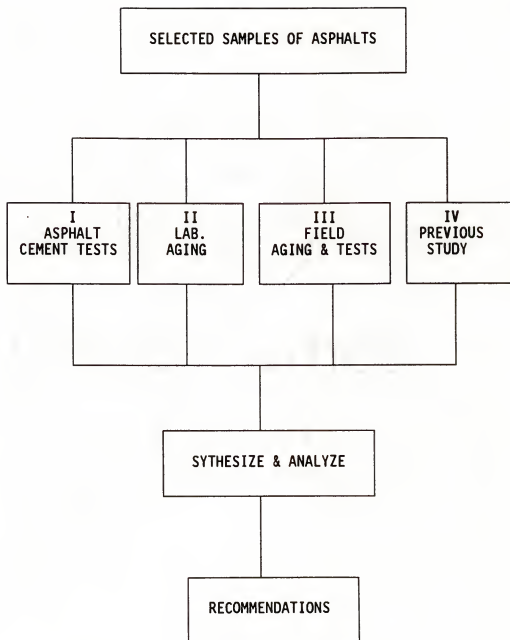


Figure 1.1 The Research Program of the Study

program to evaluate their aging characteristics. Figure 1.2 shows the testing program of the asphalt cement tests. For each of the asphalts, the following tests were performed on the asphalts and the asphalt residues after the TFOT and RTFOT at 285, 325, and 365 °F:

- a. Penetration at 77 °F.
- b. Absolute viscosity at 140 °F.
- c. Infrared spectroscopy to determine the carbonyl ratio.
- d. Schweyer rheometer at 41 and 77 °F.

1.3.2 Testing Program on Asphalt Mixtures

Of the twenty asphalts evaluated in the asphalt cement tests, five asphalts were used in a laboratory testing program to establish a relationship between mixture properties and the binder properties. Figure 1.3 shows the testing program of the asphalt mixtures. Each of these five asphalts was used to make Florida S-1 asphalt concrete mixtures, and Marshall specimens were fabricated from these mixtures. The compacted asphalt mix specimens were subjected to the following aging conditions:

- a. Aging in convectional oven at 140 °F for 14, 28, and 90 days.
- b. Aging in forced-draft oven at 140 °F for 14, 28, and 90 days.
- c. Aging in ultraviolet oven at 140 °F for 14, 28, and 90 days.
- d. Aging under natural sunlight for 3, 6, 12, 24, and 48 months.
- e. No aging.

Four replicate specimens were made for each condition. The following tests were run on the Marshall specimens at the various aging conditions:

- a. Resilient modulus tests at 41, and 77 °F.

BLOCK I

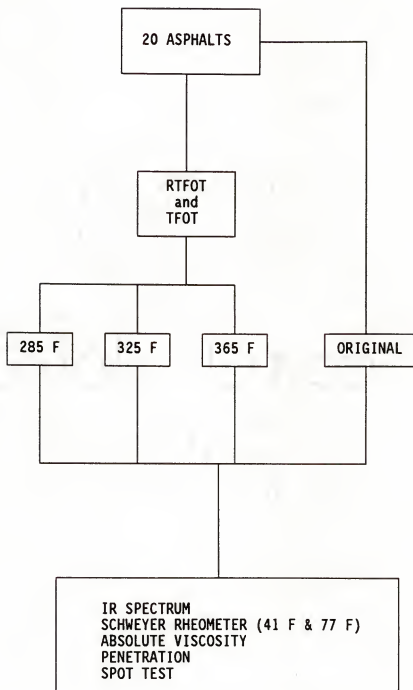


Figure 1.2 The Testing Program of the Asphalt Cement Tests

BLOCK II

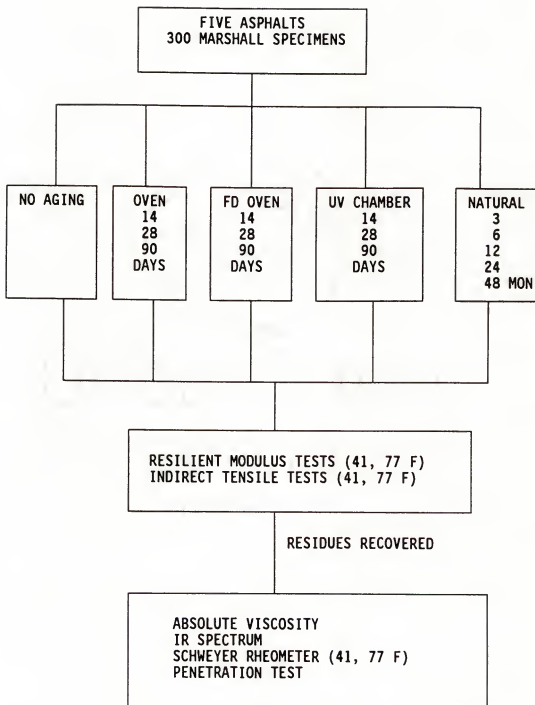


Figure 1.3 The Testing Program of the Asphalt Mixtures

- b. Indirect tensile test at 41 °F
- c. Indirect tensile test at 77 °F.

After the specimens were broken in the indirect tensile tests, asphalt residues were recovered from the asphalt mixtures, and the following tests were performed on the recovered asphalt residues and the original asphalts:

- a. Absolute viscosity at 140 °F
- b. IR spectral analysis
- c. Schweyer rheometer test at 59 and 77 °F
- d. Penetration at 77 °F.
- e. Spot test

1.3.3 Testing of Field Samples from Paving Projects

Core samples were obtained from three paving projects. The core samples were evaluated in the indirect tensile test for their resilient moduli at 41 and 77 °F and their indirect tensile strength and fracture energy at 41 and 77 °F. The testing program is shown in Figure 1.4.

The asphalts were recovered from the core samples and the following tests were performed on the recovered asphalts:

- a. Absolute viscosity at 140 °F
- b. IR spectral analysis
- c. Schweyer rheometer test at 59 and 77 °F
- e. Penetration at 77 °F.

BLOCK III

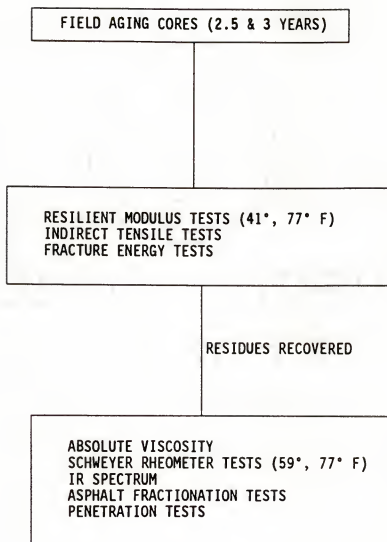


Figure 1.4 The Testing Program of the Field Samples

CHAPTER 2 LITERATURE REVIEW

2.1 Distress in Asphalt Concrete Pavements

The types and causes of distress in asphalt concrete pavements vary with the environmental and geological conditions encountered in the construction of highways. Table 2.1 gives a listing of the primary types and causes of pavement distress [2]. Table 2.2 shows the classification system of types and causes of asphalt pavement failures [3]. From these tables, the failure of asphalt concrete pavement can be categorized into three major groups: disintegration, cracking, and rutting.

2.1.1 Disintegration

Disintegration is the gradual breakup of the asphalt pavement under the abrasive action of traffic and under the mechanical or chemical actions of weathering [3]. It is evidenced by the wearing or breaking away (ravelling) of loosened material from the surface of the pavement. It is obvious that an age-hardened and embrittled asphalt is one of the reasons for disintegration of asphalt concrete pavement.

2.1.2 Cracking of the Flexible Pavement

Cracking of flexible pavements has been categorized into two broad types, i.e., low temperature cracking and fatigue cracking.

Low temperature cracking. Low temperature cracking has been recognized as the most common non-traffic associated failure mode and is

TABLE 2.1 Primary Types and Causes of Distress
in Asphalt Concrete Pavements [2]

TYPE OF DISTRESS	CAUSES OR CONTRIBUTING FACTORS
1. Rutting	- Consolidation Shear failure Low stability Abrasion Traffic High temperatures
2. Thermal Cracking	- Thermal contraction Shrinkage Low temperatures Fast rate of cooling Excessively hard asphalts Lack of snow cover (insulation)
3. Load Associated or Fatigue cracking	- Traffic - volume and loads Deflection basin characteristics: 1. Layer moduli 2. Layer thickness 3. Asphalt viscosity Climate-Microclimate 1. Temperature 2. Drainage-moisture variations Material quality
4. Combined Thermal and Induced Cracking	- Combine factors in items 2 and 3
5. Heaving - (Localized or Extensive: Frost Boils, Ice lenses)	- Expansive soils Frost susceptible soils Drainage Permeability Capillarity Depth and rate of frost penetration
6. Settlement and Slope Failures	- Quality of insitu materials Quality of construction Drainage and moisture conditions Mining activity Karst terrain - sinkholes and cavity collapse

TABLE 2.2 Classification System of Types and Causes of Asphalt Pavement Failures [3]

TYPES OF FAILURES	CAUSES OF FAILURES	
	Primary	Contributing
Disintegration	Low cohesion	soft asphalt poor aggregate grading low density
	Low abrasion resistance	insufficient asphalt brittle asphalt soft aggregate chairs and studs
	Debonding of asphalt/aggregate	hydrophilic aggregate displacement of asphalt by water displacement of asphalt by solvent displacement of asphalt mix by jet blast
Instability	Low interparticle friction	excess asphalt smooth, polished agg. clay-water present
	Low mass stiffness	soft binder poor aggregate grading (insufficient rock) insufficient fines
	Low density	insufficient compaction cold compaction improper compaction
	Changing foundation support	differential settlement differential expansion frost heave trenching

TABLE 2.2 -- Continued

TYPES OF FAILURES	CAUSES OF FAILURES	
	Primary	Contributing
Fracture (Cracking)	Shrinkage	absorptive aggregate aging asphalt temperature fluctuations volume change of coatings (paint, jet seals, mud, etc.)
	Brittleness	asphalt embrittlement burned asphalt brittle base (e.g. cement-treated) low-temperature exposure
	Fatigue	resilient or "springy" base inadequate pavement stiffness channelized traffic poor drainage of pavement section
	Slippage	insufficient bond between layer low tensile strength of overlay thin overlay no lateral support (e.g. shoulders)
	Reflection	shrinkage forces shear forces bending stresses/ strains
	Settlement & Heave	fill settlement (deep) expansive soils

a serious problem in many locations of relatively cold climates [4,5,6,7]. The problem is basically related to the occurrence of low temperatures, which induces tensile stresses in the pavement materials, which, in turn, results in fracture. It has been found that cracking increases as the environmental conditions become colder. Because of pavement geometries, the principal axis of contraction is in the longitudinal direction, therefore, the majority of thermal cracks are in the transverse direction.

Several researchers have postulated that cracking occurs when the thermally induced tensile stresses equal the tensile strength of the asphalt concrete [8,9,10,11]. The rheological properties of the asphalt at low temperatures are generally considered the most important factor in low temperature transverse cracking [4,12,13,14]. Many researchers have associated low temperature cracking with properties such as asphalt stiffness, viscosity, temperature susceptibility, and glass transition temperature. All researchers have found that the stiffer and more temperature susceptible the asphalt, the greater the potential is for cracking.

Many researchers have conducted investigations on the subject of reducing cracking. It has been found that pavements using asphalts with low viscosity and low temperature susceptibility exhibit less cracking [12,13,14]. Still another consideration is the potential effect on permanent deformation resulting from the use of a softer asphalt to resist cracking [11]. Asphalt content and thickness of asphalt pavement are also factors that influence low temperature transverse cracking, but the influences are of a lesser degree than those of asphalt properties [12,14]. An increased AC content can reduce the low temperature

transverse cracking. Also, less low temperature cracking occurs in thicker pavement than it does in thinner pavement.

Fatigue cracking. The most prevalent mode of distress in flexible pavements in the United States has been reported as fatigue cracking resulting from repeated traffic loads [3,15]. Fatigue distress is the phenomenon of fracture under repeated stresses which are less than the tensile strength of the material.

Fatigue characterization of materials has been studied extensively. However, the approach to the analysis and design of asphalt concrete pavements based on fatigue concept has not been based on actual response of the pavement. Design procedures based on fatigue assume that there is some average pavement condition for which an equivalent amount of damage will be incurred under each passing wheel load. These procedures neglect that deflections, strains, and stresses cover a wide spectrum of values dependent on temperature and climatic fluctuations. In these procedures, the variable properties of asphalts at low temperatures are not properly considered.

Several researchers have proposed modifications to fatigue life predictions based on temperature, recognizing that the fatigue life of materials tested in the laboratory is dependent on temperature [16]. It has also been found that fatigue life is highly dependent on the type of fatigue test performed [10,11]. Investigators recently have found that rest periods markedly increase the fatigue life of bituminous mixtures [17]. This seems to indicate that asphalt concrete has the potential to heal, or that the actual failure mode is not a true fatigue phenomenon. Both of these ideas negate the validity of conventional fatigue approaches.

2.1.3 Rutting of Asphalt Concrete Pavements

Rutting is accumulated permanent deformation of the pavement in the wheelpaths which results from the repeated application of wheel loads. Rutting can occur in any or all of the layer of an asphalt concrete pavement structure [10,11,18-27]. The degree of rutting is a function of the weight and volume of trucks using the pavement, the contact pressure of the truck tires, the properties of the asphalt concrete mix, and the environmental conditions.

There are two types of rutting that exist in asphalt concrete pavements, i.e., consolidation rutting and transverse shoving (lateral distortion). Consolidation rutting is characterized by a pure vertical compression of the asphalt concrete mix in the wheelpaths under the action of truck tires. This rutting is caused primarily by the consolidation, settlement, or compression of the pavement layers. Basically it is because of a lack of compaction of the asphalt concrete mix during the construction of the pavement. Since the amount of consolidation rutting that can occur is very small, this rutting is not a major problem in asphalt concrete pavements. The second type of rutting, transverse shoving, is definitely a significant problem in asphalt concrete pavement. There are several factors affecting the transverse rutting of asphalt concrete pavement. One major factor is related to the heavy traffic and the high tire pressure of the truck tires.

The factors that contribute to rutting have been divided into three primary areas: (1) truck traffic, (2) asphalt concrete mix design, and (3) construction operations. The overloads and the increase in

contact pressure are major factors in the increase in rutting of asphalt concrete pavement.

The amount of rutting that might occur in an asphalt concrete mixture can be affected by the properties of the asphalt cement that is used in the mix. The resistance of the mix to rutting is increased as the a) viscosity grade of the asphalt cement is increased, b) temperature susceptibility of the material is reduced, and c) amount of age hardening of the asphalt cement in the mix is increased, all other factors being held constant. However, the properties of the asphalt cement used in the mix probably play a relatively smaller role in the degree of rutting. The properties of the aggregate in the mix are the major factors affecting the resistance of the mix to rutting. The shape, surface texture, and strength of the aggregate affect the interlocking of the aggregate particles and the strength of the asphalt concrete mix. The gradation of the aggregates, both coarse and fine, plays a very dominant role in the susceptibility of the mix to rutting. If the gradation is so dense that there is not enough room in the mix for the asphalt cement, the mix may be easily distorted. If the gradation plot has a hump in the gradation near the #40 sieve as compared to the maximum density gradation plot, the mix will be very sensitive to shear loading and subsequent rutting [18,19]. Furthermore, if the amount of material passing the #200 sieve is too high, the resistance of the mix to rutting can be decreased significantly.

The asphalt concrete mix itself must have the ability to withstand rutting. The air void content of the mix must be high enough to prevent bleeding due to temperature increases, but also low enough to prevent excessive hardening of the asphalt cement, fatigue failure,

moisture damage, excessive consolidation, and raveling. Also, the mix must have sufficient stability and flexibility to withstand the effects of traffic loads.

With regards to construction operations for placing asphalt concrete, a lack of density is a primary factor that contributes to rutting. Air content of the compacted mix must not be too high or too low.

2.2 Rheology of Asphalt Cement

The engineering profession has generally pursued design and analysis functions without having a good knowledge of materials properties and the factors which define failure. In the field of flexible pavement, probably the most neglected aspect of materials is the time dependent deformation or creep response which occurs when a material is subjected to static and/or dynamic loads. In many situations, a material that can creep adequately to relax stresses induced by differential settlement, thermal or drying shrinkage, etc., is desirable to prevent or minimize cracking of the flexible pavement. Therefore, knowledge of the rheological properties of bituminous materials is very important to pavement engineers.

Rheology involves the study and evaluation of the time-temperature dependent response of materials which are stressed or subjected to an applied force. The major deficiency in current asphalt specifications is the lack of low temperature specifications to minimize thermal and load induced cracking of flexible pavements. Low temperature (25° C or less) rheological properties of bitumens have been evaluated in various research investigations using testing equipment such as the sliding

plate microviscometer, co-axial viscometer, mechanical spectrometer, Schwyer constant stress rheometer, etc. However, there are no specifications for low temperature properties using these direct measurement devices.

In general, as the temperature is lowered, asphalts become more viscous and eventually exhibit glassiness [28]. At temperature higher than 60° C, the asphalt behaves as a fluid that may or may not be Newtonian. At temperature below the glass transition temperature, the asphalt behaves as an elastic solid. At intermediate temperatures, the asphalt exhibits viscoelastic behavior. Schwyer and Burns [29] found that the glass transition temperature for a wide variety of asphalts is between -10° C and 5° C.

Several rheological models that combine Hookean springs and Newtonian dashpots have been proposed to describe the behavior of asphalts [30]. Asphalt behavior is commonly described in terms of rheological parameters, and can usually be described in terms of three rheological parameters: consistency or viscosity, shear susceptibility, and temperature susceptibility [31].

However, the measurement of viscosity at low temperature often poses a problem because the asphalt behaves like an elastic material with relatively low creep deformation rates. This means an extremely long time is required for creep or viscosity tests at low stress levels. High stress levels are necessary to obtain measurements within a reasonable time interval. But if the material is shear susceptible the results may not be representative of the behavior of the material at service stress level.

Schweyer presented a pictorial review of an extensive number of devices that have been used over the years to measure rheological properties [32]. In general, the traditional transient rheometers are not directly adaptable to low temperature work [33]. However, several special testing devices have been used to conduct investigations of asphalt properties at low temperatures. These have led to improved understanding of low temperature asphalt behavior. Several investigators have concluded that low temperature asphalt properties can not be predicted from properties measured at higher temperatures. Schweyer et al. [34] found that different asphalts demonstrate very different low temperature rheological properties. In their study, it was emphasized that temperature susceptibility in the near transition region can and should be evaluated by absolute viscosity measurements rather than by empirical tests. They also stated that temperature susceptibility can not be predicted from behavior exhibited at higher temperatures.

Schmidt [35] investigated the reliability of standard ASTM tests to predict low temperature stiffness of mixtures made with a wide variety of asphalts. He concluded that low temperature thermally induced cracking should not be implied from high temperature viscosity measurements on diverse types of asphalts. Although many researchers have found reasonable correlation between measured stiffness and observed field cracking, relatively poor agreement has been obtained by researchers estimating low temperature stiffness by means of tests at higher temperatures. Keyser and Ruth [36] also emphasized the importance of experimental measurements rather than the use of empirical extrapolations to determine low temperature properties.

The development of the Schwyer constant stress rheometer is probably the most significant contribution to the understanding of low temperature response and failure properties of asphalts and asphalt mixtures [37,38]. Schwyer established rheological concepts that led to a definitive rheological model and methods to evaluate important parameters that relate to low temperature behavior. The proposed rheological model is the Burns-Schwyer model [34]. The model is a Burgers model with a modified dashpot to incorporate a self-generating feedback system to regulate the rate of viscous flow. Thus, the model accounts for viscous behavior for both Newtonian and shear susceptible materials, as well as for elastic, and delayed elastic behavior. Ruth and Schwyer [39] reported that the Burns-Schwyer model gives accurate prediction of the rheological properties of asphalts, including those that are very shear susceptible. Keyser and Ruth [36] concluded that the Schwyer rheometer is an excellent device for low temperature measurements of asphalt properties and that the concepts developed by Schwyer provide values more closely related to shear and strain rates encountered in the laboratory and in actual pavements.

2.3 Asphalt Hardening

Asphalt durability has been defined as resistance to change in original properties, for the worse, during construction and in-service aging [3]. The behavior of asphalt pavements can be greatly influenced by the durability characteristic of asphalt component. One of the major factors affecting the durability of an asphalt is its rate of hardening in service. As the asphalt ages, it gradually becomes harder and more brittle. Consequently, the pavement begins to exhibit

deficiencies, or, in other words, undesirable performance features, leading eventually to failures. The age hardening of an asphalt has been known to be caused by oxidation, loss of volatile fractions, and changes in chemical structure resulting from exposure to air, heat, and ultraviolet light.

Corbett and Schweyer [40] reported that crude source is a variable affecting both the composition and the corresponding flow properties of the original asphalt used in paving. It was estimated that there are as many as 600 different compositions being used today in North America. In the investigation in Saskatchewan, Culley found that there was a relationship between asphalt source or refinery and the amount of transverse cracking [41]. He reported that the largest changes in asphalt properties occurred during mixing in the pugmill and during 12 months of service rather than during any other handling phase. However, some asphalts were affected more by mixing than in situ aging and vice versa.

The reaction of asphalt with atmospheric oxygen (oxidation) is a major factor leading to the hardening and embrittlement of asphalt [42]. Coons and Wright found that the top quarter inch of the pavement had a viscosity 50 percent greater than at depths of one-half inch [43]. Hardening of the surface is generally greater due to greater availability of higher temperature and ultraviolet light. The rate of thermal oxidation was approximately doubled for every 10° C rise in temperature [44]. In the study done by Gietz and Lamb [45], increased hardening and oxidation were observed in pavements with high air void content and existing lateral cracking. And increased hardening was also noted with age where samples were taken periodically after initial construction. Goode and Lufsey [46] found that air permeability or air

void content, per se, do not appear to be factors affecting the rate of asphalt hardening. Air voids combined with asphalt film thickness, does appear to be an important factor affecting the rate of asphalt hardening. Page et al. [47] concluded that when considering air void content at some selected age, the recovered asphalt viscosity or penetration usually indicated harder asphalts for high air voids content samples.

The common durability tests, such as immersion compression or Marshall immersion tests, are limited only to short periods of hot-water immersion [48]. Several other durability tests were considered inadequate in accurately predicting the field aging effects [49]. Santucci and Schmidt [50] suggested that it might be dangerous to predict long term durability from short term hardening characteristics. Page et al. [47] reported that the prediction or simulation of in-service hardening appears to be feasible by using the asphalt in mixtures compacted to different air void contents and then subjected to heating in an oven at 60° C for 12 hours. Also, they found that the effect of plant mix temperature on hardening were considered proportional to the TFOT temperature. From the study of Tia et al. [1], it was found that the infrared spectroscopic techniques could be used to sensitively assess changes in the asphalt due to increased levels of oxidation.

2.4 Infrared Absorption Spectroscopy

2.4.1 Background

The technique of infrared absorption spectroscopy was developed rapidly in the United States after the end of World War II. The

technique is used extensively for the investigation of molecular structure and the analysis of functional groups.

The basic principle of this method is that interaction of infrared electromagnetic radiation with mass results in absorption of certain wavelengths of radiation, the energy of which is, in some way, related to the energy states of the molecules or groups of atoms within the molecules. In the spectrum produced, the absorption intensity is recorded as a function of wave number or wavelength; specific groups of atoms in the molecules give rise to characteristic absorption bands whose wave numbers fall within a definite range regardless of the composition of the remainder of the molecules. This constancy of absorption wave numbers makes possible the determination of functional groups present in the substance being analyzed. From the exact value of the wave numbers at which absorption is observed, conclusions may be drawn about the influence of adjacent groups in the molecule or in neighboring molecules on the vibration of the group in question. It is then possible to create a picture of the molecular configuration and to determine details of the probable structure. Because of the great variety of possible vibrations in most molecules, it is practically impossible to find two different compounds that have identical spectra. For this reason, the infrared spectrum is often referred to as a 'fingerprint' of a molecule [51]. If a large enough library of spectra is available, it is possible to identify compounds by comparison with such reference spectra.

2.4.2 Functional Groups of Asphalt

The chemical analysis of asphalts is always a big challenge to asphalt chemists because of the wide variety of molecular types and

structures present and their relatively high molecular weight. Because the number of molecules in asphalt with different chemical structures and reactivities is extremely large, determination of asphalt composition by separation of asphalt into molecular components is generally considered impractical [52]. However, if one considers the different chemical functionalities that comprise and dominate the properties of the various asphalt molecules, the number of types of functionalities that need be considered narrows to a manageable number.

The principal cause of age hardening and embrittlement of asphalt used in pavements is the atmospheric oxidation of certain asphalt molecules with the formation of highly polar and strongly interacting chemical functional groups containing oxygen [52]. Therefore, the ability to identify and quantify asphalt chemical functionality provides an important tool for assessing the effects of composition on asphalt properties and the performance of the asphalt in service. Some of the important functional groups which are an integral part of large asphalt molecules are

Naturally Occurring	Formed on Oxidation Aging
Polynuclear Aromatic	Sulfoxide
Phenolic	Anhydride
2 - Quinoline Type	Carboxylic Acid
Pyrrolic	Ketone
Pyridinic	
Sulfide	
Carboxylic Acid	

2.4.3 Infrared Spectroscopic Analysis of Asphalts

Beitchman [53] described a method for the preparation, irradiation and infrared analysis of thin films of air blown asphalts, and found that increases in absorption at wavelengths of 2.91 microns (wave number of 3430 cm^{-1}), 5.88 microns (1700 cm^{-1}), and 9.71 microns (1030 cm^{-1}) were produced by exposure of unsupported films of asphalt to the radiant energy of a carbon arc. In the study done by Greenfield and Wright [54], "carbonyl index" was used to describe the change in absorption of the carbonyl band. Twenty-four asphalts were evaluated in this study and with the exception of certain modified asphalts, an inverse relationship was shown for cycles to failure versus increase in carbonyl index. In discussing the relationship between carbonyl index and durability, Greenfield and Wright concluded that when very high oxidation results are obtained for a fixed irradiation period, the carbonyl index is limited as an indicator of durability. Unusually high values of change in absorbance may or may not indicate poor durability. Low value, however, are excellent indicators of good durability.

Wright and Campbell [54] used methods similar to that of Beitchman [53] to study the oxidation rate of eight air blown asphalts. While all the asphalts oxidized at different rates, those from the same geographical areas had similar rates; those from different areas differed considerably. An inverse relationship was found between the rate of oxidation and the accelerated weathering durability of each asphalt. The results of this study indicated that the infrared spectra of asphalt films can be used to measure the oxidation rate rapidly and accurately.

In the research work done by Tia et. al. [1], it was concluded that the infrared spectroscopic techniques can be used to sensitively assess changes in the asphalt due to increased levels of oxidation. The factor which can be used to follow these changes was obtained by dividing the ratio of absorbance at 1700 cm^{-1} for the asphalt residue, by the ratio of absorbance at 1700 cm^{-1} of the original asphalt. This value was termed the Ketone Factor, which increases with increasing levels of oxidative hardening of the asphalt. This technique of quantifying age hardening is simple and reliable for the asphalts used in their study.

From a study of available literature on the subject [42,52,55-58], it was found that the IR absorption spectra could be a useful technique for following relative changes in the level of asphalt oxidation. The carbonyl absorption region between 1600 cm^{-1} and 1900 cm^{-1} would be of particular interest since it contains the absorption bands for carboxylic acids, ketones, and anhydrides. Ketones and anhydrides are formed on oxidative aging and carboxylic acids occur naturally in the asphalt but increase on oxidative aging. These three functional groups are the most significant chemical functionalities which are an integral part of large asphalt molecules and which can be related to oxidative aging.

From the study, some major characteristics of spectra obtained from 5 wt/vol percent solutions in THF can be summarized as follows:

1. Free carbonyl absorption of acid types occurs at about 1730 cm^{-1} .
2. Free carbonyl absorption of 2-quinoline types occurs at about 1685 cm^{-1} .

3. A broad band centering at about 1600 cm^{-1} results primarily from aromatic carbon-carbon double bonds.

4. An increase in the level of oxidation causes an increase in carbonyl absorption of carboxylic acid at about 1730 cm^{-1} .

5. An increase in the level of oxidation causes a significant increase in carbonyl absorption in the 1700 cm^{-1} region, which is due to the formation of ketones and anhydrides.

2.5 Development of Asphalt Durability Tests

2.5.1 Background

Tests and evaluation methods were developed in order to ensure suitable asphalts were used in the pavement construction. Methods used by various investigators include use of high temperatures, light, chemical oxidation agents, and oxidation in solution under oxygen pressure [60,61]. Welborn [61] summarizes the various test conditions, such as temperature and exposure time, used for the aging methods along with evaluation parameters.

With the early use of asphalt in pavements, some mixes resulted in excellent pavements and some were partial or total failures. The chemists and engineers soon realized that specification requirements for asphalts, mixtures, and construction practices were essential to high quality and durability. During the early 1900s numerous laboratory-accelerated aging tests were used or proposed to assure more uniform and more durable asphalt pavements. The test conditions for heating varied from 212 to 400° F (100 to 204° C) and the time of heating varied from 30 minutes to 30 hours. The loss in weight and penetration of the residues were usually determined to measure the effect of aging.

During the 1920s, the following three national specifications for asphalt cements were published:

1. Federal specifications, adopted in 1925;
2. AASHTO specifications, adopted in 1924, revised in 1926; and
3. ASTM specifications, adopted in 1922 to 1926, withdrawn in 1939, and reissued in 1947.

With minor exceptions, the requirements for physical and chemical properties were essentially the same for the three national specifications. The specification tests included:

- Penetration,
- Flash point,
- Ductility,
- Loss at 325° F,
- Penetration of residue, percent of original,
- Bitumen, solubility in CS_2 ,
- Bitumen, solubility in CCL_4 .

The only requirements in the three specifications that might be indicative of durability were the percentage of loss on heating and penetration of the residue. However, based on a survey of asphalt production in the United States in 1935 the results of percentage of loss and of original penetration were of little value to predict the resistance to change in heating during plant mixing or during service in the pavement.

2.5.2 Tests for Asphalt Durability

In the 1930s, a large number of studies were initiated to develop methods to measure or predict the durability of asphalt cements. One of the most important breakthroughs was the development of a method by Gene

Abson in 1933 for recovering the asphalt from mixtures. Since its development, the recovery test has been used extensively in studies to determine change in asphalts and to related the changes to asphalt durability.

Laboratory-Accelerated Tests and Evaluation Methods. Asphalt aging was determined by oven volatilization, by air blowing at high temperatures, or by aging asphalt mixtures and testing the recovered asphalt. In most cases the effects of the aging procedures were evaluated by penetration and ductility. Table 2.3 gives tests and evaluation methods used along with the investigators.

Laboratory Microfilm Tests and Evaluation Methods. During the development of tests to measure and predict durability, there was considerable concern with testing the asphalts in relatively thick films such as those used in the TFO test and air-blowing tests listed in Table 2.3. Thus, beginning in the 1950s several studies were made to develop testing apparatus and to age and test asphalts in microfilm thicknesses. Table 2.4 shows several modifications of the microfilm test. In general the studies have indicated that the microfilm tests can be used to measure and predict hardening of asphalts under laboratory and field conditions.

In the effort of developing a test that would age asphalts in a film thinner than that in the 1/8 inch TFO test, California developed a rolling thin-film oven (RTFO) test. Tests have shown that the hardening effects are comparable to the hardening in the TFO test.

In a study by Kemp and Predoehl [49], the RTFO test has been modified to heat the bottle with the oven slightly tilted to prevent asphalt build-up. Studies indicate that the tilt-oven asphalt

Table 2.3. Laboratory Accelerated Test and Evaluation Methods to Determine Asphalt Durability [61]

Date	Investigator	Test Method	Evaluation Method
1903	Dow	30 hr, 400°F	Change in weight pen. of residue
1903	Dow	Mixture aged for 30 min, 300°F	Recoverd asphalt, change in pen.
1937	Nicholson	Air blowing, 15 min., 425°F	Pen., ductility
1937	Rashig and Doyle	Air blowing, 15 min., 400°F	Change in pen.
1937	Hubbard and Gollumb	Mixture, time, temp. varied	Recovered asphalt, change in pen.
1939	Lang and Thomas	Mixture, oven, outdoor exposure	Change in mix properties
1940	Shattuck	Mixture, oven, 30 min., 325°F	Recovered asphalt, pen., ductility, soft point
1940	Lewis and Welborn	1/8 in. film oven test, 5 hr, 325°F	Change in weight, pen., ductility
1946	Lewis and Halstead	1/8 in. film oven test, 5 hr, 325°F	Change in weight, pen., ductility
1952	Pauls and Welborn	Mixture, oven aging, 325°F (TFOT)	Compressive strength, recovered asphalt, TFOT residues

Table 2.4 Laboratory Microfilm and Evaluation Methods to Determine Asphalt Durability [61]

Date	Investigator	Test Method	Evaluation Method
1955	Griffin et al.	Shell microfilm test, 5 micron film, 2 hr, 225°F	Viscosity before and after aging, aging index
1958	Heithaus & Johnson	Road Tests, Lab. aging, microfilm test	Recovered asphalts, microfilm index
1961	Traxler	TFOT and micro-film, 15 micron film, 2 hr, 225°F	Microviscosity at 77°F compared
1961	Halstead & Zenewitz	TFOT & 15 micron film, 2 hr, 22°F	Microviscosity at 77°F compared
1963	Hveem et al.	Shell microfilm test, modified; 20 micron film 24 hr, 210°F	Microviscosity at 77°F before and after aging
1963	Hveem et al.	RTFOT and TFOT	Viscosities of RTFOT, TFOT, and recovered asphalts compared
1969	Schmidt & Santucci	RTFOT, 20 micron film, 210°F	Microviscosity of residue
1981	Kemp & Predoehl	Tilt-oven test 168 hr, 235°F	Pen., 77°F ductility, 77°F

durability test could be used to predict asphalt hardening in desert climates.

Field Test and Evaluation Methods to Determine Asphalt

Durability. Information from field test can be used to correlate with the physical properties of the recovered asphalt. The development of the Abson method for recovering asphalt from paving mixtures prompted many of the studies. In 1979, an NCHRP study [62] concluded that the hardness of asphalt in the pavement is the one property most closely associated with pavement performance and depends on

1. The initial consistency of the asphalt,
2. The susceptibility of the asphalt to hardening during plant mixing, and
3. The rate of hardening of the asphalt in the pavement.

In summary, the TFOT and RTFOT tests have served to screen out or predict the behavior of those asphalts that showed excessive change in physical properties when subjected to the high temperatures encountered in hot-plant mix construction. But they do not provide adequate information on change in properties during service in the pavement. In order to develop performance-related specifications for asphalt pavement, such information is essential. To accomplish this, Welborn [61] suggested that the following approaches should be investigated:

1. Evaluation of the present TFO tests to determine whether modifications are necessary to conform with current asphalts and construction practices,
2. Investigation of current or new methods that can be used to predict long-term durability of asphalts in pavements, and
3. Investigation of the use of tensile strength and resilient-

modulus properties of asphalt paving mixtures to predict asphalt durability during long-term exposure in pavements.

CHAPTER 3 EQUIPMENT AND FACILITIES

This chapter describes the equipment and facilities which were used to provide various types of aging conditions for asphalt specimens in this study. The testing equipment utilized for the strength, rheology and spectral tests are also presented.

3.1 Ultraviolet Chamber

Ultraviolet light has been used to simulate aging effects of sunlight for asphalt in this research project. This section describes the ultraviolet chamber used in the research.

Ultraviolet fluorescent sun lamps, 40-watt fluorescent UV-B lamps (UVB-313) manufactured by the Q-Panel Company, were used in the chamber. Electrically, these lamps are the same as 48 inch fluorescent lamps, but their output is quite different. The UV lamps produce largely UV, with little energy spent in the production of visible light. Since the photochemical effectiveness of light increases with decreasing wavelengths, ultraviolet light is the controlling factor in polymer deterioration. Because the special lamps produce only UV, they cause rapid material deterioration despite their low wattage.

The chamber was made from 3/8 inch plywood in the shape of a trapezoidal box with a 4'2" x 3' 9 1/2" rectangular base and a height of 1' 10". The two sides of the chamber were hinged to permit access into the chamber and the interiors of these two hinged sides were used to

mount four lamp assemblies, each assembly carrying two lamps. The roof of the chamber was used to mount one more lamp assembly carrying two lamps. Aluminum sheeting was fixed to the base of the chamber in order to prevent staining of the woodwork and to increase reflection. Figure 3.1 illustrates the chamber. A picture of the chamber is shown in Figure 3.2.

The destructive effects of UV exposure are accelerated when temperature is increased. Although temperature does not affect primary photochemical reactions, it does affect secondary reactions. Therefore, a typical temperature condition of 60° C (140° F) was maintained in the chamber. To maintain the temperature, a thermostat was installed with the sensor located at midpoint of the sample area. Heating arrangement consisted of three lamps mounted on one vertical side of the chamber. One of the lamps was an infrared heatlamp (Warm Up), manufactured by General Electric Company. The other two lamps were plant lights (Gro and Sho 150 watt bulbs), also manufactured by General Electric Company. Circulation of heat was improved by a fan installed at the opposite end of the chamber. Also, a dummy specimen with thermistor inside was used to monitor specimen temperature.

3.1.1 Lamp Mounting and Rotation

Lamps are arranged in two sets of four lamps each on the interior sides of the chamber, and two more lamps on the top interior. Since fluorescent lamps are diffuse light sources, this arrangement provides uniform irradiation of the test surface.

Since the output of the lamps reduces as the lamps age, it is necessary to replace and rotate the lamps periodically. This was done by replacing two of the lamps at intervals of 360 hours and rotating the

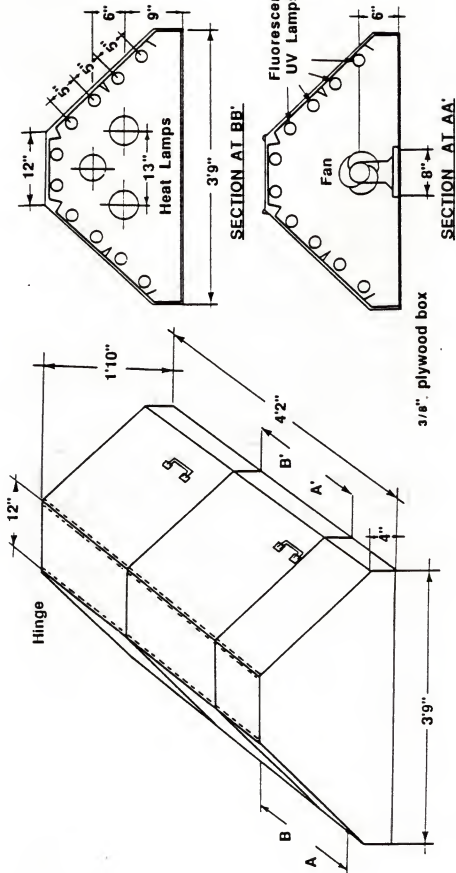


Figure 3.1 Ultraviolet Chamber



Figure 3.2 Picture of the Ultraviolet Chamber

position of the rest as illustrated in Figure 3.3. The rotation and replacement of the lamps ensure stable UV output as the lamps age.

3.2 Forced Draft Oven

The forced draft oven was made by modifying a standard laboratory oven to enable air flow through the oven. This was done by providing a large inlet port on one side of the oven and a small exit port on the top of the oven. These two ports were connected externally by flexible aluminum duct. A 375 cfm air booster was used to circulate the air in the oven. The oven temperature was maintained at 60° C (140° F) by using a thermostat switch and sensor. Figure 3.4 shows the forced draft oven.

3.3 Convectional Oven

A standard laboratory convection oven was used to age the specimens at a stable temperature of 60° C (140° F). Thermometers were installed and the temperature was monitored regularly.

3.4 MTS Closed Loop Hydraulic Testing System

The MTS closed loop hydraulic testing system was used to perform the resilient modulus, indirect tensile and fracture energy tests. The system consisted mainly of a control unit, load frame, load cell, servovalve and hydraulic power supply. Figure 3.5 shows the MTS system.

Two stainless steel loading strips 1/2 in. wide were used to apply the load to the specimen as shown in Figure 3.6. The loading strips were curved at the interface with the specimen with a radius of 2 in.

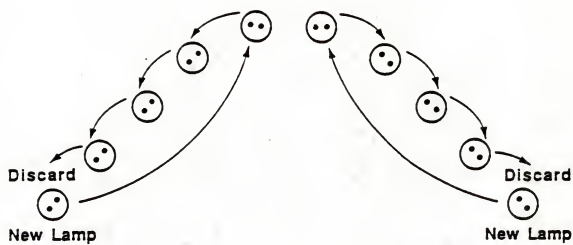


Figure 3.3 Rotation of Lamps in UV Chamber



Figure 3.4 Picture of the Forced Draft Oven



Figure 3.5 Picture of MTS Machine

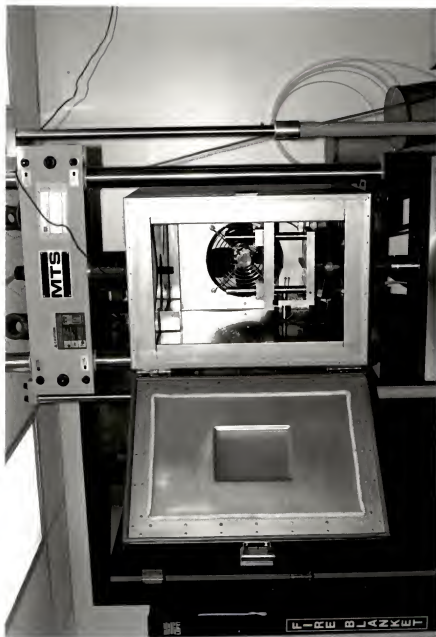


Figure 3.6 Picture of Loading Arrangement

Two guide rods were used to prevent any eccentricity in loading. The horizontal deformations of the specimen were measured by two identical Linear Variable Differential Transformers (LVDTs) mounted on opposite sides of the specimen. The output voltages of the LVDTs and the load cell were calibrated and connected to a multi-channel drum chart recorder.

3.5 Constant Stress Rheometer

3.5.1 General

The development of the Schwyer constant stress rheometer with its capability of measuring rheological properties at -10°C or lower has produced information which has improved our understanding of low temperature cracking problems. Furthermore, the rheological concepts established by H.E. Schwyer has culminated in a definitive rheological mode and methods to evaluate important parameters such as shear modulus, viscosity, and stiffness.

A Cannon Schwyer Constant Stress Rheometer was used in this research. Figure 3.7 shows the rheometer. A schematic of the test set-up is shown in Figure 3.8.

The rheometer consists of a nitrogen gas operated pneumatic cylinder which applied a specific force to the plunger in the sample tube. A LVDT measured the movement of the plunger and the output voltage was digitized and acquired by a data analysis system. The data system was operated on a IBM 9000 mini computer (see Figure 3.9).

The basic operation of the rheometer is fairly simple. A sample tube is filled to approximately 2 to 6 mm from the top of the sample tube. The plunger is inserted into the sample tube and the entire



Figure 3.7 Picture of Cannon Schwyer Rheometer

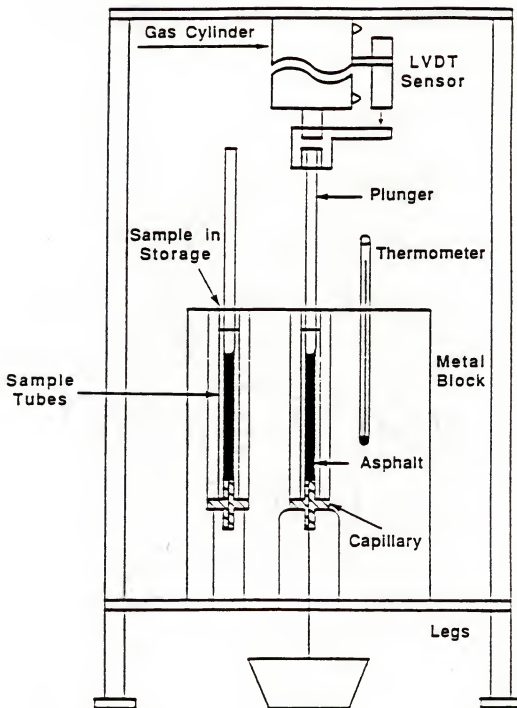


Figure 3.8 Schematic of Cannon-Schweyer Rheometer



Figure 3.9 Picture of IBM 9000 Mini Computer

assembly placed into an insulated aluminum block, which has been cooled to the desired testing temperature. Once the temperature has stabilized, the gas pressure is preset and gas cylinder activated to apply force to the plunger and asphalt sample. The deformation vs. time plot is recorded for each stress level until the response becomes linear. Tests are usually conducted at a minimum of 5 stress levels.

Two types of rheometer tube can be used. The first type is a plug flow tube with a uniform diameter, while the second type is a sample tube with capillary. Equations for computation of shear stress and shear rate in the constant stress rheometer test are based on the assumption of steady laminar flow in a tube.

3.5.2 Data acquisition system for the Schwyer rheometer test

The data acquisition system used for the Schwyer Rheometer test consists of a Schwyer Rheometer, measuring devices (LVDT and transducer), a Ready/Run Box, a 4-channel Analog Breakout Box, an Analog Sensor Board, and an IBM 9000 System mini computer. The schematic of this system is shown in Figure 3.10.

The Linear Differential Transformer (LVDT) is used to measure the movement of the plunger when the pressure is applied to the asphalt sample. The Analog Sensor Board is used as an interface between the IBM 9000 System computer and the measuring devices. The output of the measuring devices is interfaced to the Sensor Board through the Ready/Run Box and the 4-channel Analog Breakout Box. The Analog Sensor Board consists of a A/D converter and a switch input driver. The A/D converter digitizes the analog output (voltage) from the measuring devices and the switch input driver is used to start the data acquisition cycle.

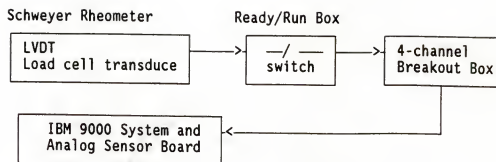


Figure 3.10 The Schematic of Data Acquisition System of the Schweyer Rheometer Test

The data acquisition program SCHWY is written in the IBM 9000 BASIC language. This language offers wide varieties of hardware accessibility and control through the use of device drivers. The IBM 9000 mini computer serves as a control computer. Once the data are collected, calculation and analysis of these data can be done by the computer. The high resolution monochrome monitor and a printer are both output devices that display pertinent data.

3.6 Infrared Spectrophotometer

3.6.1 Fourier Transform Infrared Spectroscopy [70]

An Fourier Transform Infrared (FTIR) spectrophotometer basically consists of two parts: an optical system which uses an interferometer and a dedicated computer. The computer controls the optical components, collects and stores data, performs computations on data and displays spectra. The advantages of an FTIR spectrophotometer result from the use of an interferometer rather than a grating or prism of a conventional spectrophotometer.

The design of the interferometer and the way in which the interferometer is operated are the major distinctions between the FTIR spectrophotometer and the conventional IR spectrophotometer. The interferometer may be operated by scanning in a discontinuous, step-wise manner (step-scan interferometer), in a slow continuous manner with chopping of the infrared beam (slow scanning), or rapidly without chopping of the infrared beam. The rapid scanning Fourier transform spectrophotometer with a Michelson interferometer seems to have emerged as the most practical form of FTIR spectrophotometer for commercial

development and widespread application to chemical problems in all regions of the infrared spectrum.

Fourier transform infrared spectroscopy provides potential advantages compared with conventional dispersion infrared spectroscopy, namely (1) higher signal-to-noise ratios for spectra obtained under conditions of equal measurement time, and (2) higher accuracy in frequency for spectra taken over a wide range of frequencies. The signal-to-noise advantage is a result both of the concurrent measurement of the detector signal for all resolution elements of the spectrum and of the high optical throughput of the FTIR spectrophotometer. The improvement in frequency accuracy of the FTIR spectrophotometer is a result of the use of a laser which references the measurements made by the interferometer. Other advantages for FTIR spectroscopy include the high operational reliability, convenient data handling, and simplicity of the optical system.

3.6.2 Testing System

The Perkin-Elmer Model 1600 Fourier Transform Infrared Spectrophotometer was used to perform the infrared spectroscopic tests (see Figure 3.11). The spectrophotometer is a bench-top instrument that provides, in one self-contained unit, all the following features:

- an electronics system based on the Motorola 68010 Central Processing Unit.
- a rapid data acquisition over a total range of 7800 to 100 cm^{-1} , with 2 cm^{-1} resolution and good signal-to-noise ratio.
- a single-beam, purgeable sample compartment.
- a dedicated keyboard for controlling the instrument and interacting with the software.



Figure 3.11 Picture of the FTIR Spectrophotometer

- a high-resolution screen for display of both results and instrument-status information.

The Spectr Tech 1.0 mm NaCl sealed cells were used in the FTIR tests. Figure 3.12 shows the sealed cell.



Figure 3.12 Picture of the Sealed Cell, Vial and Syringe

CHAPTER 4 MATERIALS AND TEST PROCEDURES

The materials and test procedures used in the testing program are described in this chapter. It includes a description of the properties of asphalts and aggregates used, the fabrication of Marshall specimens, the various laboratory aging conditions, the tests on Marshall specimens, and the tests on the aged asphalt residues.

4.1 Materials

4.1.1 Asphalts

Twenty representative asphalts commonly used in Florida and its neighboring states were selected and used in the testing program. The selected asphalts are shown in Table 4.1.

4.1.2 Aggregates

The aggregates used for Marshall specimens were obtained from V. E. Whitehurst and Sons, Inc. in Gainesville. The four types of aggregate were blended in equal quarters (25% each) to meet the specification of Florida Type S-1 mix. Table 4.2 shows the aggregate types used for asphalt concrete mixtures.

4.1.3 Marshall Specimens

Five of the twenty asphalts evaluated in the asphalt cement tests were used to make Florida Type S-1 asphalt concrete mixes and Marshall

Table 4.1 Asphalts Used in This Study

ASPHALT	ABBREVIATION
1. MARIANI AC-30 A	MA30A
2. MARIANI AC-30 B	MA30B
3. MARIANI AC-30 C	MA30C
4. MARIANI AC-30 D	MA30D
5. MARIANI AC-30 E	MA30E
6. MARIANI AC-20 TRIFINERY	MA20T
7. MARIANI AC-20 CURACAO	MA20C
8. MARIANI AC-20 VENEZUELAN	MA20V
9. COATAL TEXAS AC-20	TL20
10. COSDEN TEXAS AC-20	TN20
11.* BELCHER JAX AC-30 ANTI-STRIP	BJ30A
12. BELCHER JAX AC-20	BJ20
13. CHEVRON JAX AC-30 ANTI-STRIP	CJ30A
14.* MARATHON TAMPA AC-30	MT30
15.* CHEVRON TAMPA AC-30	CT30
16. TRUMBULL AC-30 ANTI-STRIP	TB30A
17. SHELL ATLANTA AC-20	SA20
18. AMOCO SAVANNAH AC-30	AS30
19.* BELCHER FT. LAUD AC-30	BF30
20.* MARIANI AC-30	MA30

* - ASPHALTS USED FOR MARSHALL SPECIMENS

Table 4.2 Aggregates Used for Asphalt Concrete Mix

MATERIAL	MATERIAL TYPE	PRODUCER
1	#67 Stone	Florida Rock Industries
2	#89 Stone	Florida Rock Industries
3	#140 Screenings	Florida Rock Industries
4	Local Sand	Whitehurst Construction Co.

specimens were fabricated from these mixes. A total of 300 Marshall specimens were fabricated, 60 specimens for each asphalt type. The asphalts used to make the Marshall specimens can be found in Table 4.1.

The gradation of the blended aggregate was checked for each type of asphalt mix. Two sieve analyses tests were run for each type of asphalt mix. The results of the sieve analysis are shown in the Table 4.3.

The Marshall specimens were fabricated with an asphalt content of 6.5 percent and compacted by the 50-blow Marshall compaction method. The Rice Method (ASTM D2041) was used to determine the maximum specific gravity of the mixes. Two tests were run for each asphalt type mix. Table 4.4 shows the results of the maximum specific gravity of the mixes. The properties of the 300 Marshall specimens are shown in Appendix A.1.

4.2 Laboratory Procedures

4.2.1 Laboratory Aging Condition

The compacted asphalt mix specimens were subjected to the following aging conditions:

- a. Aging in convectional oven at 140° F for 14, 28, and 90 days.
- b. Aging in forced-draft oven at 140° F for 14, 28, and 90 days.
- c. Aging in ultraviolet oven at 140° F for 14, 28, and 90 days.
- d. Aging under natural sunlight for 3, 6, 12, 24, and 48 months.
- e. No aging.

Table 4.3
Results of Sieve Analysis on the Aggregate Used
for the Marshall Specimens
(Percent Passing, Wet Sieve)

SIEVE NO.	3/4"	1/2"	3/8"	#4	#10	#40	#80	#200
S-1 SPEC.	100	88-100	75-93	47-75	31-53	19-35	7-21	2-7
BJ1	100	95.06	81.47	60.25	44.01	28.66	8.74	4.11
BJ2	100	95.40	84.20	62.10	43.90	27.80	7.50	4.10
MT1	100	96.68	87.12	61.16	44.79	28.62	7.79	4.88
MT2	100	92.34	80.00	58.17	44.56	29.70	8.38	3.86
CT1	100	94.57	83.97	56.63	44.37	29.46	8.08	5.88
CT2	100	95.50	82.34	58.15	41.78	27.96	7.77	6.08
BF1	100	94.50	82.00	63.84	43.99	28.08	7.52	3.40
BF2	100	96.28	83.03	62.24	41.65	27.37	7.10	3.28
MA1	100	95.13	84.49	58.17	46.03	29.84	8.88	6.91
MA2	100	96.75	84.50	57.36	42.45	28.96	7.89	6.36

Table 4.4 Maximum Specific Gravities of Mixtures

MIXTURE	MAXIMUM SPECIFIC GRAVITY
BF1	2.2992
BF2	2.2991
MT1	2.2897
MT2	2.2836
CT1	2.3013
CT2	2.2936
BJ1	2.3060
BJ2	2.3176
MA1	2.2979
MA2	2.2916

4.2.2 Randomization in Assignment of Treatments

The assignment of specimens to different groups for various aging conditions was done by using the random numbers for general sampling procedure in the Asphalt Paving Manual [59]. The differences between the average densities of the different groups of specimens in a specific type of mix were found to be statistically insignificant. Therefore, the effects of different air voids would not affect the effects of different aging environments. The exposure assignments of the Marshall specimens are shown in Appendix A.2.

4.3 Schweyer Rheometer Test

4.3.1 Procedure for analysis of Schweyer rheometer data

This section describes the procedures used for analysis of Schweyer rheometer data. Only the main equations are given in this section. The detailed derivation of the equations and procedures can be found in reference 38.

The shear stress (τ') and shear rate ($\dot{\gamma}'$) before applying geometry and Rabinowitsch corrections are computed for all the stress levels tested. The uncorrected shear stress is computed by the following equation [38]

$$\tau' = K_r F, \text{ Pa} \quad (4.1)$$

where

$K_r = 1/(\pi DL)$ for plug flow tube with uniform diameter

$K_r = D_c/(\pi L_c D_c^2)$ for sample tube with capillary

F = plunger force, N

The uncorrected shear rate is computed by the equation:

$$\gamma' = K V, \text{ s}^{-1} \quad (4.2)$$

where

$K = 8/D$ for plug flow tube with uniform diameter

$K = 8D_t^2/(D_c)^3$ for sample tube with capillary

V = velocity of flow in the sample tube

The $\log \tau'$ (shear stress) versus $\log \gamma'$ (shear rate) plot of this data should be a straight line (conforming to the power law). The computed shear stress and shear rate before applying geometry and Rabinowitsch corrections, are plotted to obtain the shear susceptibility factor (C). Next the viscosity at 1.0 sec^{-1} is computed using both geometry (G) and Rabinowitsch (R) correction factors:

$$\eta_{1.0} = \frac{\tau' G}{(R \times \gamma')^C} \quad (4.3)$$

Theoretically, any set of τ' and γ' values may be used to compute η_1 . Having computed $\eta_{1.0}$ it is possible to compute the viscosity (η_i) at any other shear rate (γ_i):

$$\eta_i = \eta_{1.0} (\gamma_i)^{C-1}$$

However, a substantial error may be induced if the viscosity is computed at a shear rate considerably different from that of the test values. For this reason, H.E. Schweyer proposed the use of a constant power input for computation of apparent viscosities. The apparent viscosity

at a constant power input of 100 watts/m^3 can be computed as:

$$n_j (\text{where } j=100 \text{ w/m}^3) = n_{1.0} \left(\frac{100}{n_{1.0}} \right)^{\frac{C-1}{C+1}}, \text{ Pa}\cdot\text{s} \quad (4.4)$$

where $j = \tau_j \dot{\gamma}_j$, constant power input, w/m^3

n_j = apparent viscosity at a constant power input of j

Viscosity measurements at one temperature are not usually sufficient to define the low temperature rheological behavior of bitumens. Therefore, it is desirable to obtain test results at different temperatures and to plot a $\log n_a$ versus $\log$ temperature curve. The plot may be based on viscosities at any desired shear rate although best results may be obtained using viscosities at constant power ($j=100 \text{ w/m}^3$). Regression analysis methods may be used to establish the line of best fit provided that the viscosity-temperature relationship is essentially linear. Equations of the following format often provided a good fit for data at temperatures below 40°C (104°F):

$$1. \log n_a = b_0 + b_1 \log (^\circ\text{K}) \quad (4.5)$$

$$2. \log n_a = b_0 + b_1 (^\circ\text{C}) \quad (4.6)$$

4.3.2 Experimental Procedures

The procedure for Schwyer constant stress rheometer test consists of the following steps:

1. A sample tube is filled with the test asphalt right to the top.
2. The plunger is seated and forced into the sample tube for about 5 mm.

3. The entire assembly is placed into the metal block, which is to be cooled or heated to the test temperature.

4. Once the temperature stabilizes, the gas pressure is preset and the gas cylinder is activated to apply force to the plunger and asphalt sample.

5. Through the data acquisition system, the creep curve is recorded for each stress level until the response becomes linear.

6. Tests are conducted at a minimum of five stress levels, usually between 100 psi and 20 psi.

7. The analysis program SCHWY2 is then used to analyze the data and to plot the shear stress versus shear rate relationship.

8. The computer program also computes the shear susceptibility (C) and constant power viscosity (η_j).

4.4 Indirect Tensile Test

4.4.1 General

The indirect tensile test is a simple and common method used to determine the tensile strength of concrete or bituminous mixtures. The test involves loading a cylindrical specimen diametrically at a constant rate until splitting failure occurs. Both the vertical and horizontal deformations are recorded during the loading process.

On the basis of the maximum load at failure P , applied through a loading strip of width $1/2$ in., the tensile strength at failure S_t , can be calculated by the expression

$$S_t = (1.96 P) / (\pi t d) \quad (4.7)$$

where

- S_t = indirect tensile strength, psi (or MPa),
P = ultimate applied load required to fail specimen, lbf (or N),
t = thickness of specimen, in. (or mm), and
d = diameter of specimen, in. (or mm).

4.4.2 Experimental Procedure

This section describes the procedures of the indirect tensile test.

1. Place the test specimens in a controlled-temperature cabinet and bring them to the specified test temperature. The test specimens should remain in the cabinet at the specified test temperature for at least 24 hours prior to testing.

2. Place a specimen into the loading apparatus and position the loading strips to be parallel and centered on the vertical diametral plane. Make sure the LVDTs touch firmly on both sides of the specimen.

3. Apply load at a rate of 2 inches per minute until failure. Both load and horizontal deformation are measured and plotted on the chart recorder.

4. The indirect tensile strength can be calculated using the formula given above.

4.5 Resilient Modulus Test

4.5.1 General

The resilient modulus is defined as the ratio of the applied stress to the recoverable strain when a repeated dynamic load is applied. Basically, the test method involves application of cyclic pulse loads of relatively short duration of time and recording the

instantaneous deformation using strain gages or linear variable differential transformers (LVDTs). The resilient moduli are then calculated from the induced stresses and the measured strains. Therefore, the resilient modulus is essentially the instantaneous elastic modulus of a viscoelastic material.

The conventional resilient modulus test is conducted in a triaxial device. Specimens are usually 4 inches in diameter and 8 inches in height. Repetitive pulse loads of constant magnitude are applied on the flat surfaces of the specimens, and the deformations are measured using LVDTs. A simpler test method is the diametral resilient modulus test developed by Schmidt [70]. In this method, standard Marshall size specimens are used. A vertical pulse load of 0.1 second duration is applied diametrically on the test specimen every 3 seconds, and the corresponding horizontal deformation is recorded.

The method proposed by Schmidt has been standardized in ASTM D4123. The application of compressive loads with a haversine or suitable wave form is recommended. The load is applied vertically in the vertical diametral plane of a cylindrical specimen through a loading strip of 1/2 inch width. The resulting horizontal deformation of the specimen is measured and, with an assumed Poisson's ratio, is used to calculate the resilient modulus.

Two resilient modulus values can be obtained from the deformation data. The instantaneous resilient modulus is calculated using the recoverable deformation that occurs instantaneously during the unloading portion of one cycle. The total resilient modulus is calculated using the total recoverable deformation which includes both the instantaneous

and recoverable and the time-dependent continuing recoverable deformation during the unloading and rest-period portion of one cycle.

The resilient moduli can be calculated by the expressions:

$$M_{RI} = P (\mu_{RI} + 0.27) / (td_{RI}) \quad (4.8)$$

$$M_{RT} = P (\mu_{RT} + 0.27) / (td_{RT}) \quad (4.9)$$

where

M_{RI} = instantaneous resilient modulus of elasticity, psi (or MPa),

M_{RT} = total resilient modulus of elasticity,
psi (or MPa) ,

μ_{RI} = instantaneous resilient Poisson's ratio,

μ_{RT} = total resilient Poisson's ratio,

P = repeated load, lbf (or N),

t = thickness of specimen, in. (or mm),

d_{RI} = instantaneous recoverable horizontal deformation, in. (or mm),

d_{RT} = total recoverable horizontal deformation, in (or mm).

A value of 0.35 for Poisson's ratio has been found to be reasonable for asphalt mixtures at 77° F (25° C) [71].

4.5.2 Experimental Procedure

This section describes the procedures of the resilient modulus test.

1. Place the test specimens in a controlled-temperature cabinet and bring them to the specified test temperature. The test specimens should remain in the cabinet at the specified test temperature for at least 24 hours prior to testing.

2. Place a specimen into the loading apparatus and position the loading strips to be parallel and centered on the vertical diametral plane. Make sure the LVDTs touch firmly on both sides of the specimen.
3. Precondition the specimen by applying a pulsating haversine load of 100 lbs at a loading frequency of 1.0 Hz with a duration of 0.1 second for 10 times.
4. Apply 10 haversine pulse loads of 200 lbs. at a loading frequency of 1.0 Hz with a duration of 0.1 second.
5. Both load and deformation are measured and plotted on the chart recorder. A typical load-pulse deformation trace is shown in Figure 4.1.
6. Rotate the test specimen 90° and repeat the test.
7. Measure the recoverable horizontal deformations. Use the average values to calculate the resilient moduli.
8. Calculate the resilient moduli using the formula mentioned above.

4.6 Fracture Energy

The induced horizontal strain and applied vertical stress were used to establish fracture energy (F_E) values using the relation

$$F_E = \sigma \epsilon \quad (4.10)$$

where

σ = applied vertical tensile stress,

ϵ = induced horizontal strain.

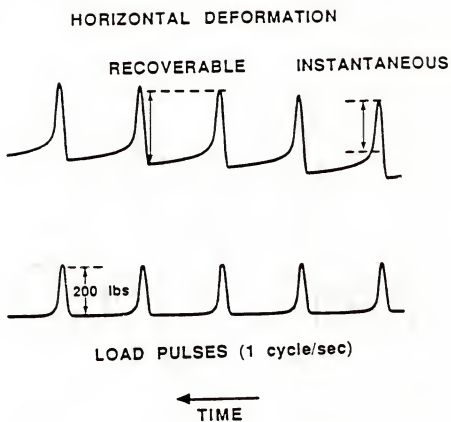


Figure 4.1 Typical Load-Pulse Deformation Trace

On the load and horizontal deformation plots recorded for the indirect tensile test, ten ordinates were chosen on the load curve and values of load measured. The first measurement was zero load and the tenth measurement was the failure load. Corresponding values of horizontal deformation were also measured.

Applied stress was calculated for each value of the load using Equation 4.7. Using the corresponding value of horizontal deformation, the elastic modulus was calculated using Equation 4.9. Poisson's ratio was taken as 0.35.

Using the calculated values of applied stress and elastic modulus, the induced strain was obtained by the relation

$$\epsilon = \sigma/E \quad (4.11)$$

Thus, for each specimen tested, ten data points became available, defining the relationship between applied vertical stress and induced horizontal strain. The area under this curvilinear relationship was calculated using the trapezoidal rule, which yielded the value of fracture energy.

4.7 Infrared Spectroscopic Test

The asphalts and residues were dissolved in Tetrahydrofuran at a concentration of 5 percent (W/V) and evaluated in the FTIR spectrophotometer. A sealed cell with 0.1 mm pathlength and sodium chloride windows was used.

The following is a brief description of the testing procedures which were adopted for the infrared spectral test.

1. Weigh out asphalt specimen, approximately 0.20 grams, in a glass vial. The weight should be accurately measured to a hundredth of a gram.
2. HPLC grade Tetrahydrofuran (THF) is used to make a 5 percent (W/V) solution. Shake the vial occasionally to accelerate the dissolving of the asphalt sample for ten minutes. (WARNING: THF is toxic; read product data and safety sheets.)
3. The sealed cell is cleaned by flushing THF through the cell. 3 cc Luer Lock syringes are used in this procedure. Then the cell is filled carefully with THF such that no air bubbles are trapped.
4. Insert the sealed cell into the cell holder in the sample compartment of the spectrophotometer. Close the sample compartment.
5. Operate the system software to scan the solvent, generating the background spectrum for THF. The background spectrum is stored on the disk facilities. Generate the background spectrum on every occasion that the test is run.
6. Remove the sealed cell. Clean and dry the cell.
7. Put the asphalt solution into the cell by using a syringe.
8. Insert the sealed cell into the cell holder in the sample compartment of the spectrophotometer. Close the sample compartment.
9. Operate the system software to scan the asphalt solution, generating the spectrum for the asphalt solution. Using software commands, the background spectrum is ratioed out, yielding the spectrum of the asphalt sample, which is stored on the disk facilities.
10. Using various software commands, the analysis of the spectrum of the asphalt is done, so as to obtain the values of absorbance at different wavenumbers.

11. The Carbonyl Ratios and Ketone Factors can be calculated using the values obtained in step 10.

12. A hardcopy of the spectrum is also obtained on a connected plotter.

13. The sealed cell and syringe are rinsed out with THF until thoroughly clean and put away when done for the day. Store the cell in a dry desiccated chamber.

CHAPTER 5 TESTS ON ASPHALT BINDERS

5.1 Introduction

Twenty representative asphalts commonly used in Florida and its neighboring states were selected to be used in a laboratory testing program to evaluate the proposed criteria for selection of asphalt for improved durability. Figure 3.2 shows the testing program on the asphalt cements. For each of the asphalts, the following tests were performed on the asphalts and the asphalt residues after the TFOT (ASTM D1754-78) and RTFOT (ASTM D2872-80) at 285, 325, and 365 °F:

- a. Penetration at 77 °F
- b. Absolute viscosity at 140 °F
- c. Infrared spectroscopy
- d. Schweyer rheometer test

5.1.1 Statistical Model for Asphalt Binder Tests

The test results from asphalt binder tests were analyzed as results of a factorial experiment comprising of twenty types of asphalts (ASPHALT), three levels of temperature (TEMP), and two types of test (OVEN). In the study, the concern is on only these twenty asphalts, three temperatures, and two tests. Therefore, ASPHALT, TEMP, and OVEN are regarded as fixed effects. The following linear model was assumed for any single measurement in the experiment:

$$Y_{ijk} = m + A_i + T_j + O_k + (AT)_{ij} + (AO)_{ik} + (TO)_{jk} + \epsilon_{ijk}$$

where

Y_{ijk} = the response of the i th ASPHALT, j th TEMP, and k th OVEN

m = the overall mean

A_i = the main effect of ASPHALT i

T_j = the main effect of TEMP j

O_k = the main effect of OVEN k

$(AT)_{ij}$ = the interaction of ASPHALT i x TEMP j

$(AO)_{ik}$ = the interaction of ASPHALT i x OVEN k

$(TO)_{jk}$ = the interaction of TEMP j x OVEN k

ϵ_{ijk} = the experimental error.

For each of the parameters tested, this analysis will yield information on the following:

- a) Differences between TFOT and RTFOT
- b) Differences between the asphalt types
- c) Differences due to the temperature effects
- d) Interaction between the asphalt types, tests, and temperatures.

5.2 Penetration Test on Asphalt Binders

The results of the penetration tests are shown in Tables 5.1 and 5.2. Figures 5.1 and 5.2 show the TFOT and RTFOT effects on percent retained of penetration. In order to increase the data base, data from a previous research [1] were included in the analyses. Table 5.3 shows the data from the previous research.

Table 5.1 TFOT and RTFOT Effects on Penetration

ASPHALT	TEST	ORIGINAL	PENETRATION AT 77°F OVEN TEMPERATURE(°F)		
			285	325	365
MA30A	TFOT	65	-	-	-
	RTFOT				
MA30B	TFOT	62	-	-	-
	RTFOT				
MA30C	TFOT	58	-	-	-
	RTFOT				
MA30D	TFOT	63	-	-	-
	RTFOT				
MA30E	TFOT	60	-	-	-
	RTFOT				
MA20T	TFOT	72	60	52	42
	RTFOT		56	51	42
MA20C	TFOT	70	53	45	35
	RTFOT		44	41	35
MA20V	TFOT	84	69	59	46
	RTFOT		64	52	45
TL20	TFOT	72	52	40	32
	RTFOT		42	34	30
TN20	TFOT	56	43	35	28
	RTFOT		41	34	29
BJ30A	TFOT	61	47	39	32
	RTFOT		41	34	28
BJ20	TFOT	70	53	43	33
	RTFOT		46	37	34
CJ30A	TFOT	66	54	45	37
	RTFOT		45	39	33
MT30	TFOT	53	44	37	31
	RTFOT		37	33	29
CT30	TFOT	57	-	-	-
	RTFOT		42	38	32
TB30A	TFOT	74	58	51	42
	RTFOT		56	45	42
SA20	TFOT	65	51	41	34
	RTFOT		41	37	33
AS30	TFOT	65	52	43	35
	RTFOT		44	39	32
BF30	TFOT	55	41	36	28
	RTFOT		36	31	28
MA30	TFOT	61	49	42	34
	RTFOT		47	38	33

Table 5.2 TFOT and RTFOT Effects on
% Penetration Retained

ASPHALT	TEST	% PENETRATION RETAINED OVEN TEMPERATURE(°F)		
		285	325	365
MA30A	TFOT	-	-	-
	RTFOT	-	-	-
MA30B	TFOT	-	-	-
	RTFOT	-	-	-
MA30C	TFOT	-	-	-
	RTFOT	-	-	-
MA30D	TFOT	-	-	-
	RTFOT	-	-	-
MA30E	TFOT	-	-	-
	RTFOT	-	-	-
MA20T	TFOT	83.3	72.2	58.3
	RTFOT	77.8	70.8	58.3
MA20C	TFOT	75.7	64.3	50.0
	RTFOT	62.9	58.6	50.0
MA20V	TFOT	82.1	70.2	54.8
	RTFOT	76.2	61.9	53.6
TL20	TFOT	72.2	55.6	44.4
	RTFOT	58.3	47.2	41.7
TN20	TFOT	76.8	62.5	50.0
	RTFOT	73.2	60.7	51.8
BJ30A	TFOT	77.0	63.9	52.5
	RTFOT	67.2	55.7	45.9
BJ20	TFOT	75.7	61.4	47.1
	RTFOT	65.7	52.9	48.6
CJ30A	TFOT	81.8	68.2	56.1
	RTFOT	68.2	59.1	50.0
MT30	TFOT	83.0	69.8	58.5
	RTFOT	69.8	62.3	54.7
CT30	TFOT	-	-	-
	RTFOT	73.7	66.7	56.1
TB30A	TFOT	78.4	68.9	56.8
	RTFOT	75.7	60.8	56.8
SA20	TFOT	78.5	63.1	52.3
	RTFOT	63.1	56.9	50.8
AS30	TFOT	80.0	66.2	53.8
	RTFOT	67.7	60.0	49.2
BF30	TFOT	74.5	65.5	50.9
	RTFOT	65.5	56.4	50.9
MA30	TFOT	80.3	68.9	55.7
	RTFOT	77.0	62.3	54.1

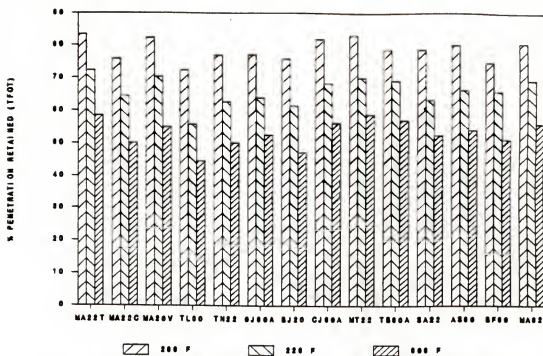


Figure 5.1 Penetration Retained vs. Oven Temperature (TFOT)

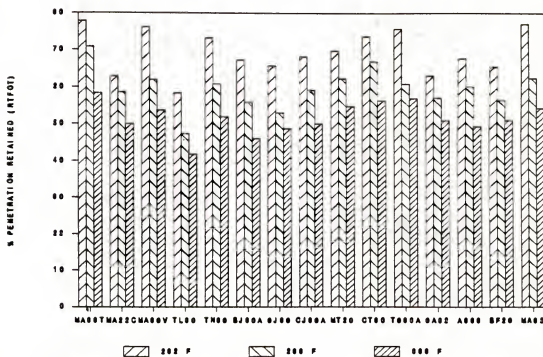


Figure 5.2 Penetration Retained vs. Oven Temperature (RTFOT)

Table 5.3 Penetration Results From Previous Research

Asphalt	Test	% Penetration Retained Oven Temperature (°F)		
		285	325	365
VB	TFOT	76.5	66.2	51.5
AC-30	RTFOT	69.1	60.3	48.5
VE	TFOT	79.1	64.2	50.7
AC-30	RTFOT	68.7	56.7	50.7
VA	TFOT	75.3	61.6	46.6
AC-30	RTFOT	68.5	56.2	46.6
VD	TFOT	75.8	66.1	56.5
AC-30	RTFOT	74.2	61.3	56.5
VC	TFOT	73.8	61.5	49.2
AC-30	RTFOT	66.2	56.9	47.7
VJ	TFOT	74.7	62.7	58.7
AC-20	RTFOT	70.7	57.3	52.0
VJ	TFOT	82.4	71.6	56.9
AC-20 Mod.	RTFOT	74.5	58.8	55.9
VG	TFOT	73.9	58.0	44.3
85-100	RTFOT	68.2	54.5	48.9
VF	TFOT	85.4	76.8	63.4
85-100	RTFOT	84.1	78.0	69.5
VI	TFOT	88.9	81.5	74.1
25-35	RTFOT	88.9	77.8	66.7
VH	TFOT	71.1	57.9	40.8
85-100	RTFOT	71.1	55.3	42.1

Since asphalts had a variety of penetration values in the original state, the percent penetration retained is more appropriate to be used for comparison. Results of ANOVA on the percent penetration retained are shown in Table 5.4. From Table 5.4, it is seen that all three main effects and the interaction effects except ASPHALT*TEMP are significant.

Since the OVEN interacts with both ASPHALT and TEMP, comparison on OVEN effect must be done for each ASPHALT at different temperature level. From Tables 5.2 and 5.3, it is seen that the RTFOT is a more severe aging process than the TFOT for oven temperatures of 285 and 325 °F. However, the two processes are not much different from each other at an oven temperature of 365 °F.

5.3 Absolute Viscosity Test on Asphalt Binders

The results of the absolute viscosity tests are shown in Tables 5.5 and 5.6. Figures 5.3 to 5.10 show the TFOT and RTFOT effects on absolute viscosity and absolute viscosity ratio. For analyses, data from a previous research [1] were included. Data from a previous research are shown in Table 5.7.

Since it is known that the asphalts are quite different from each other in their original viscosities, comparison of asphalts by viscosity values after TFOT and RTFOT would be more appropriate if the viscosity ratios are considered.

Results of ANOVA on the absolute viscosity ratio are summarized in Table 5.8. From Table 5.8, it is seen that all three main effects and the interaction ASPHALT*TEMP are significant. Since OVEN does not interact with ASPHALT and TEMP, the OVEN can be evaluated by comparing

Table 5.4 ANOVA on PEN Retained

Source	DF	Mean Square	F Value	Pr > F
ASPHALT	25	193.30075	46.53	0.0001
TEMP	2	6056.51418	1457.87	0.0001
OVEN	1	847.64310	204.04	0.0001
ASPHALT*TEMP	50	5.60310	1.35	0.1500
ASPHALT*OVEN	24	14.04473	3.38	0.0002
TEMP*OVEN	2	128.80673	31.01	0.0001

R-Square: 0.989

Table 5.5 TFOT and RTFOT Effects on Absolute Viscosity

ASPHALT	TEST	ORIGINAL	ABSOLUTE VISCOSITY AT 140°F OVEN TEMPERATURE		
			285	325	365
MA30A	TFOT	3245	5068	6924	11776
	RTFOT		5789	8712	12135
MA30B	TFOT	3258	5421	8968	13237
	RTFOT		6614	9622	16243
MA30C	TFOT	3549	5229	7991	16384
	RTFOT		6762	10649	17149
MA30D	TFOT	3290	5883	9474	19796
	RTFOT		7688	13515	23200
MA30E	TFOT	3053	4941	7693	14110
	RTFOT		5877	9394	14435
MA20T	TFOT	2606	3631	4996	7496
	RTFOT		4082	5571	7714
MA20C	TFOT	2861	4731	7148	13420
	RTFOT		5995	8699	13597
MA20V	TFOT	2563	4113	7223	13105
	RTFOT		4870	7302	13673
TL20	TFOT	1863	3676	6961	15884
	RTFOT		5184	9211	16838
TN20	TFOT	2028	3221	4586	7516
	RTFOT		3497	4959	7559
BJ30A	TFOT	3335	5043	7848	15501
	RTFOT		6782	11893	24079
BJ20	TFOT	1976	3367	5290	11727
	RTFOT		4691	7291	10783
CJ30A	TFOT	2965	4856	6836	11648
	RTFOT		6498	8535	13681
MT30	TFOT	3410	5740	8472	16429
	RTFOT		8148	11965	17832
CT30	TFOT	2890	4973	6996	10599
	RTFOT		6423	9228	12285
TB30A	TFOT	3175	5842	9594	19253
	RTFOT		7174	12089	17734
SA20	TFOT	2057	3583	5618	9878
	RTFOT		4804	6964	9786
AS30	TFOT	3421	5247	8192	13493
	RTFOT		6384	9414	13504
BF30	TFOT	4130	5482	7924	12267
	RTFOT		6793	9998	12267
MA30	TFOT	3202	4756	6958	10583
	RTFOT		5923	8511	11492

Table 5.6 TFOT and RTFOT Effect on
Absolute Viscosity Ratio

ASPHALT	TEST	ABSOLUTE VISCOSITY RATIO OVEN TEMPERATURE(°F)		
		285	325	365
MA30A	TFOT	1.56	2.13	3.63
	RTFOT	1.78	2.68	3.74
MA30B	TFOT	1.66	2.75	4.06
	RTFOT	2.03	2.95	4.99
MA30C	TFOT	1.47	2.25	4.62
	RTFOT	1.91	3.00	4.83
MA30D	TFOT	1.79	2.88	6.02
	RTFOT	2.34	4.11	7.05
MA30E	TFOT	1.62	2.52	4.62
	RTFOT	1.92	3.08	4.73
MA20T	TFOT	1.39	1.92	2.88
	RTFOT	1.57	2.14	2.96
MA20C	TFOT	1.65	2.50	4.69
	RTFOT	2.10	3.04	4.75
MA20V	TFOT	1.60	2.82	5.11
	RTFOT	1.90	2.85	5.33
TL20	TFOT	1.97	3.74	8.53
	RTFOT	2.78	4.94	9.04
TN20	TFOT	1.59	2.26	3.71
	RTFOT	1.72	2.45	3.73
BJ30A	TFOT	1.51	2.35	4.65
	RTFOT	2.03	3.57	7.22
BJ20	TFOT	1.70	2.68	5.93
	RTFOT	2.37	3.69	5.46
CJ30A	TFOT	1.64	2.31	3.93
	RTFOT	2.19	2.88	4.61
MT30	TFOT	1.68	2.48	4.82
	RTFOT	2.39	3.51	5.23
CT30	TFOT	1.72	2.42	3.67
	RTFOT	2.22	3.19	4.25
TB30A	TFOT	1.84	3.02	6.06
	RTFOT	2.26	3.81	5.59
SA20	TFOT	1.74	2.73	4.80
	RTFOT	2.34	3.39	4.76
AS30	TFOT	1.53	2.39	3.94
	RTFOT	1.87	2.75	3.95
BF30	TFOT	1.33	1.92	2.97
	RTFOT	1.64	2.42	2.97
MA30	TFOT	1.49	2.17	3.31
	RTFOT	1.85	2.66	3.59

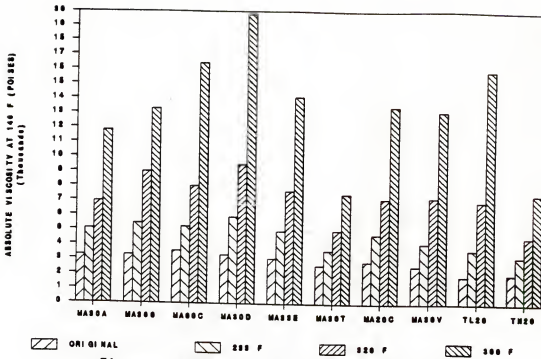


Figure 5.3 Effect of TFOT on Absolute Viscosity

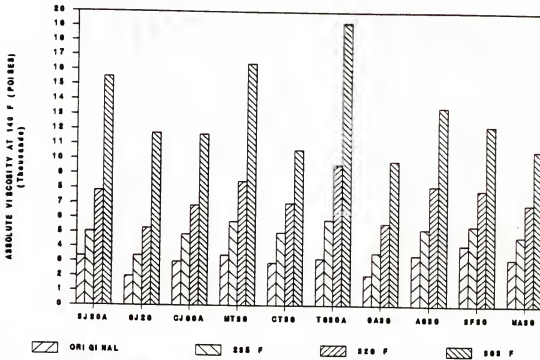


Figure 5.4 Effect of TFOT on Absolute Viscosity

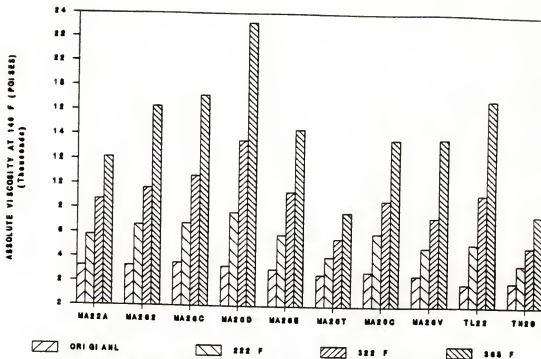


Figure 5.5 Effect of RTFOT on Absolute viscosity

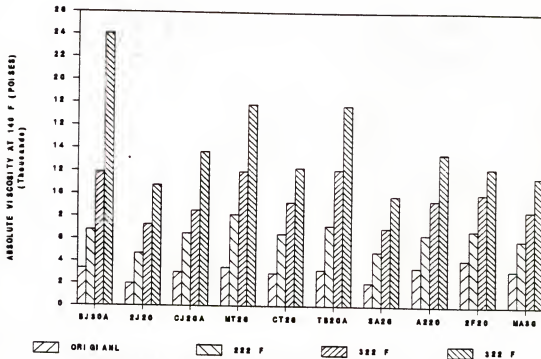


Figure 5.6 Effect of RTFOT on Absolute viscosity

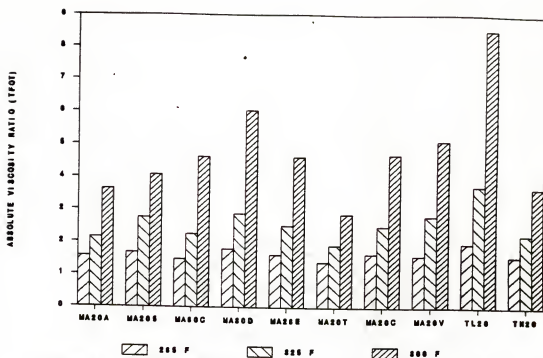


Figure 5.7 Absolute Viscosity Ratio vs. Oven Temperature (TFOT)

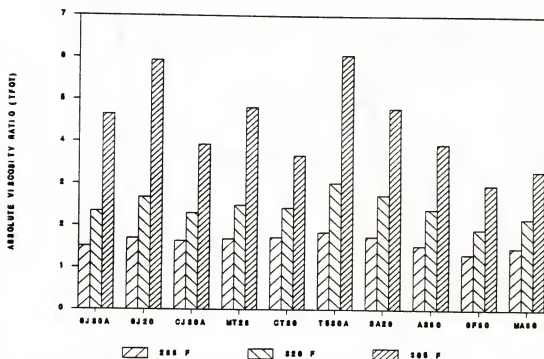


Figure 5.8 Absolute Viscosity Ratio vs. Oven Temperature (TFOT)

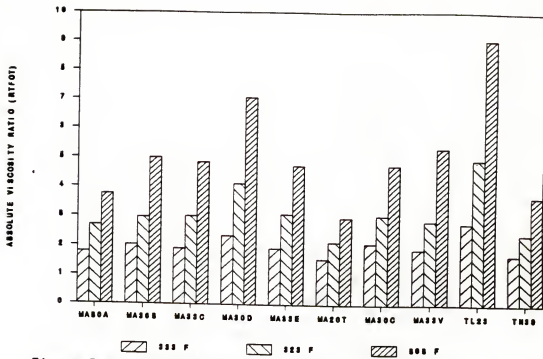


Figure 5.9 Absolute Viscosity Ratio vs. Oven Temperature (RTFOT)

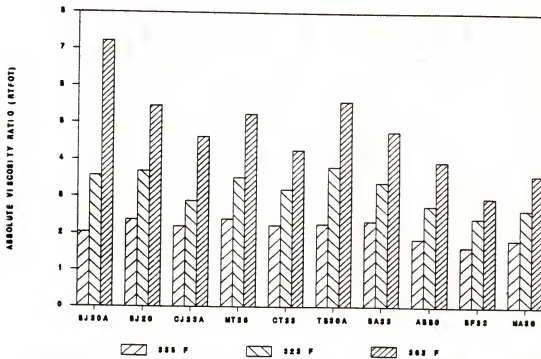


Figure 5.10 Absolute Viscosity Ratio vs. Oven Temperature (RTFOT)

Table 5.7 Absolute Viscosity Results from Previous Research

Asphalt	Test	Absolute Viscosity Ratio Oven Temperature (°F)		
		285	325	365
VB	TFOT	1.98	3.14	7.33
AC-30	RTFOT	2.49	4.64	10.60
VE	TFOT	2.03	3.23	8.42
AC-30	RTFOT	2.41	4.11	7.86
VA	TFOT	1.77	2.96	7.15
AC-30	RTFOT	2.11	3.17	5.47
VD	TFOT	1.72	2.57	4.57
AC-30	RTFOT	1.96	2.86	4.76
VC	TFOT	1.90	3.19	7.98
AC-30	RTFOT	2.54	3.94	8.73
VJ	TFOT	1.85	2.93	6.02
AC-20	RTFOT	2.07	3.93	4.78
VJ	TFOT	1.48	1.91	3.94
AC-20 Mod.	RTFOT	1.97	3.53	4.74
VG	TFOT	1.51	2.19	3.80
85-100	RTFOT	1.78	2.35	3.06
VF	TFOT	1.37	1.86	3.07
85-100	RTFOT	1.48	1.77	2.47
VI	TFOT	1.47	2.14	3.93
25-35	RTFOT	1.60	2.72	6.49
VH	TFOT	2.36	4.70	21.40
85-100	RTFOT	2.38	5.01	13.95

Table 5.8 ANOVA on Absolute Viscosity Ratio

Source	DF	Mean Square	F Value	P r > F
ASPHALT	30	8.7368643	19.12	0.0001
OVEN	1	6.3215274	13.84	0.0004
TEMP	2	216.2998651	473.40	0.0001
ASPHALT*TEMP	60	3.9948567	8.74	0.0001
ASPHALT*OVEN	30	0.6934641	1.52	0.0848
OVEN*TEMP	2	1.3043145	2.85	0.0654

R-Square: 0.972

the mean responses for the two types of oven, averaged over the other two factors.

Comparison on the two types of oven was done at three different levels of temperature. This was done by Duncan's multiple-range test at a level of significance of 0.05. The results are shown in Table 5.9. From Table 5.9, it is seen that the RTFOT is a more severe aging process than the TFOT for oven temperatures of 285 and 325 °F. However, for an oven temperature of 365 °F, the two processes are not significantly different from one another.

5.4 Infrared Spectroscopy on Asphalt Binders

Study of the infrared absorption spectra indicates that there is a definite increase in the infrared absorbance in the 1700 cm^{-1} region as the level of oxidation increases. This is due to increasing concentration of ketones and anhydrides. Also, infrared absorbance of acid types occurs at about 1730 cm^{-1} . Ketones and anhydrides are formed on oxidative aging and carboxylic acids occur naturally in the asphalt but increase on oxidation aging. Since these three functional groups are the most significant chemical functionalities which can be related to oxidative aging, examination of the spectra in this study was done with particular reference to them.

The spectra also indicated that the band centering at about 1600 cm^{-1} which results primarily from aromatic carbon-carbon double bonds, can be assumed to be fairly constant, because the group is present in highly condensed stable molecules [63]. Therefore, the Carbonyl Ratio, which is a ratio of absorbance at 1700 cm^{-1} and 1600 cm^{-1} , can be used to express the level of oxidation.

Table 5.9 Comparison on TFOT and RTFOT
at Three Temperature Levels

TEMP.	Duncan Grouping	Mean	N	OVEN
285°F	A	2.0645	31	RTFOT
	B	1.6748	31	TFOT
325°F	A	3.2626	31	RTFOT
	B	2.6148	31	TFOT
365°F	A	5.538	31	RTFOT
	A	5.470	31	TFOT

* Means with the same letter are not significantly different.

The results of the infrared spectroscopy are shown in Table 5.10. Figures 5.11 to 5.14 show the effect of TFOT and RTFOT on the Carbonyl Ratio. Results of ANOVA on the data are summarized in Table 5.11. From Table 5.11, it is seen that all three main effects and interaction effects are significant.

Comparison on the effect of OVEN was done at different temperature levels. This was done by Duncan's multiple-range test at a level of significance of 0.05. The results are summarized in Table 5.12. From Table 5.12, it is seen that the effects of TFOT and RTFOT are not significantly different from each other at oven temperatures of 285 and 325 °F. But at 365 °F, the TFOT is a more severe aging process than the RTFOT from the stand point of Carbonyl Ratio.

5.5 Schwyer Rheometer Test on Asphalt Binders

Table 5.13 shows the results of Schwyer rheometer test on the original asphalts. Nine of the twenty asphalts were used in the Schwyer rheometer test. The results are shown in Table 5.14. Results of ANOVA on the rheometer test are summarized in Table 5.15. From Table 5.15, it is seen that the OVEN effect is not significant.

The constant power viscosity vs. temperature relationships for the original asphalts are shown in Figure 5.15 and 5.16. It can be seen that asphalts of the same grade at high temperature (60 °C) can have very different properties at lower temperature. Figures 5.17 to 5.25 show the TFOT effect on the constant power viscosity vs. temperature relationships for each asphalts. It is seen that the asphalt constant power viscosity-temperature relationship is shifted parallel to the original relationship after TFOT. The degree of parallel shifting

Table 5.10 Results of Infrared Spectroscopy

ASPHALT ORIGINAL	TFOT 285°F	TFOT 325°F	TFOT 365°F
MA30A	0.3543	0.3480	0.3668
MA30B	0.2548	0.2984	0.3231
MA30C	0.2551	0.2530	0.2914
MA30D	0.2737	0.3126	0.3479
MA30E	0.3081	0.3619	0.3675
MA20T	0.3775	0.3764	0.4320
MA20C	0.3540	0.3861	0.4338
MA20V	0.3512	0.3742	0.4075
TL20	0.3250	0.3644	0.3924
TN20	0.2444	0.2627	0.2958
BJ30A	0.3370	0.2933	0.3256
BJ20	0.3171	0.3321	0.3660
CJ30A	0.3050	0.3468	0.3650
MT30	0.3282	0.3126	0.3421
CT30	0.3584	0.3975	0.4469
TB30A	0.4314	0.4529	0.4971
SA20	0.3178	0.3620	0.3980
AS30	0.3971	0.3741	0.4114
BF30	0.3673	0.3831	0.4279
MA30	0.3277	0.3404	0.3678
VB	0.2840	0.3410	0.3680
VE	0.3210	0.3520	0.3670
VA	0.2850	0.3310	0.3680
VD	0.3130	0.3470	0.3820
VC	0.3150	0.3600	0.3860
VJ	0.2820	0.3190	0.3490
VJM	0.2820	0.2960	0.3150
VG	0.2540	0.2800	0.3100
VF	0.7480	0.8050	0.8210
VI	0.3590	0.3740	0.3870
VH	0.3660	0.4030	0.4140

Table 5.10 --Continued

ASPHALT	ORIGINAL	RTFOT 285°F	RTFOT 325°F	RTFOT 365°F
MA30A	0.3543	0.3545	0.3680	0.3711
MA30B	0.2548	0.2812	0.3206	0.3683
MA30C	0.2551	0.2030	0.2487	0.2868
MA30D	0.2737	0.3102	0.3443	0.3684
MA30E	0.3081	0.3207	0.3568	0.3867
MA20T	0.3775	0.3836	0.4236	0.4516
MA20C	0.3540	0.3995	0.4467	0.4736
MA20V	0.3512	0.3951	0.4121	0.4360
TL20	0.3250	0.3753	0.3920	0.4244
TN20	0.2444	0.2479	0.2726	0.3066
BJ30A	0.3370	0.3033	0.3359	0.3761
BJ20	0.3171	0.3421	0.3708	0.3931
CJ30A	0.3050	0.3653	0.3866	0.4073
MT30	0.3282	0.3286	0.3360	0.3577
CT30	0.3584	0.3807	0.3890	0.4288
TB30A	0.4314	0.4496	0.4512	0.4774
SA20	0.3178	0.3557	0.3791	0.4044
AS30	0.3971	0.3892	0.4373	0.4643
BF30	0.3673	0.3987	0.4366	0.4601
MA30	0.3277	0.3401	0.3607	0.3870
VB	0.2840	0.3240	0.3660	0.3920
VE	0.3210	0.3230	0.3490	0.4120
VA	0.2850	0.3530	0.3620	0.4260
VD	0.3130	0.3180	0.3600	0.3760
VC	0.3150	0.3370	0.3670	0.4110
VJ	0.2820	0.3240	0.3540	0.3630
VJM	0.2820	0.2930	0.3160	0.3580
VG	0.2540	0.2790	0.3260	0.3390
VF	0.7480	0.7930	0.8380	0.8580
VI	0.3590	0.3760	0.4090	0.4740
VH	0.3660	0.3930	0.4180	0.4580

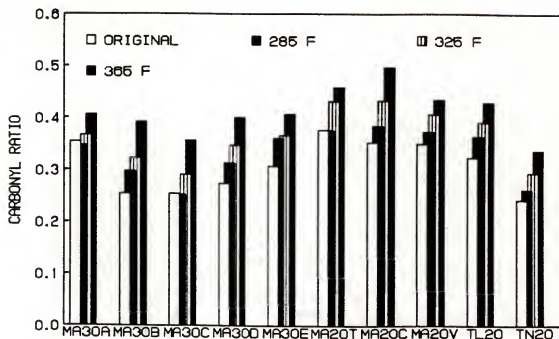


Figure 5.11 Carbonyl Ratio vs. Oven Temperature (TFOT)

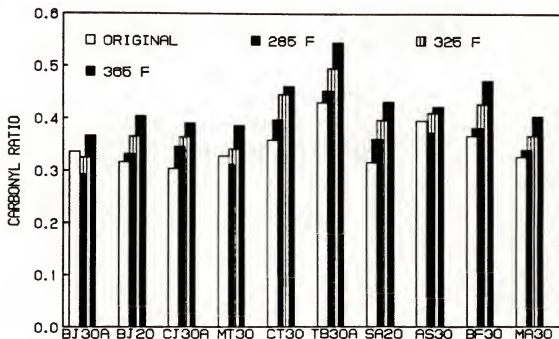


Figure 5.12 Carbonyl Ratio vs. Oven Temperature (TFOT)

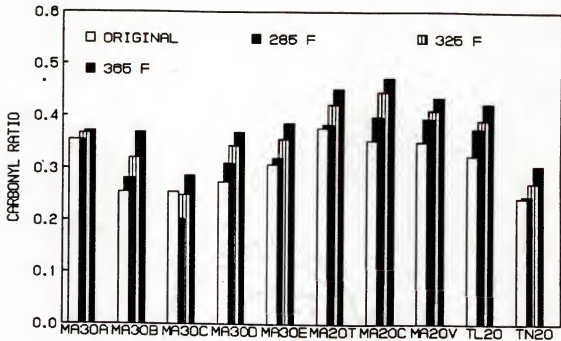


Figure 5.13 Carbonyl Ratio vs. Oven Temperature (RTFOT)

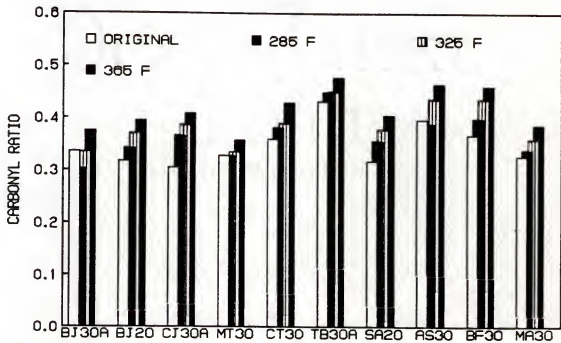


Figure 5.14 Carbonyl Ratio vs. Oven Temperature (RTFOT)

Table 5.11 ANOVA on the Infrared Spectroscopy Results

SOURCE	DF	ANOVA SS	F VALUE	PR > F
ASPHALT	30	1.57990015	646.54	0.0
TEMP	2	0.14249844	874.71	0.0
OVEN	1	0.00360800	44.29	0.0001
ASPHALT*TEMP	60	0.00950103	1.94	0.0055
ASPHALT*OVEN	30	0.01348053	5.52	0.0001
TEMP*OVEN	2	0.00223958	13.75	0.0001

Table 5.12 Comparison of Carbonyl Ratio on the TFOT and RTFOT

TEMP.	DUNCAN GROUPING	MEAN	N	OVEN
285°F	A	0.359371	31	TFOT
	A	0.356042	31	RTFOT
325°F	A	0.389452	31	TFOT
	A	0.384955	31	RTFOT
365°F	A	0.434623	31	TFOT
	B	0.416023	31	RTFOT

* Means with the same letter are not significantly different.

Table 5.13 Results of Schweyer Rheometer Test on Original Asphalts

ASPHALT	C VALUE		Nj (Pas)	
	41°F	77°F	41°F	77°F
MA30A	0.78	0.99	105559000	225715
	0.83	1.00	89936900	188550
MA30B	1.11	1.02	74156400	342260
	1.09	1.09	89563200	278806
MA30C	0.63	0.89	226055000	416123
	0.72	0.90	159718000	359387
MA30D	0.61	0.92	136696000	386520
	0.57	0.85	244281000	394638
MA30E	0.87	1.16	153100000	202829
	0.93	1.10	116200000	210183
MA20T	1.17	1.01	63108600	102577
	1.14	1.00	62118000	159926
MA20C	0.99	0.90	78002200	515192
	1.05	0.87	45416900	691512
MA20V	0.89	0.99	54533000	220698
	0.86	0.95	60670800	192815
TL20	0.29	0.97	1778310000	281662
	0.28	1.01	1875600000	167020
TN20	0.79	0.92	487279000	951524
	0.82	1.07	482526000	536071
BJ30A	0.79	0.99	113312000	264961
	0.94	0.89	67216800	408088
BJ20	0.83	0.78	111734000	544280
	0.85	0.73	113379000	748936
CJ30A	0.62	0.99	286575000	349691
	0.61	1.03	278523000	301660
MT30	0.64	0.85	252477000	471541
	0.63	0.85	258437000	486388
CT30	0.78	0.87	105307000	408446
	0.68	0.82	176288000	677324
TB30A	0.72	0.64	36108400	836738
	0.57	0.64	62694200	876500
SA20	0.24	0.91	1638560000	239055
	0.26	0.92	1946950000	370852
AS30	0.47	1.06	1104530000	209811
	0.45	1.01	1111200000	256713
BF30	0.70	1.14	610784000	243592
	0.68	1.04	613913000	345046
MA30	0.68	0.94	230442000	482422
	0.78	0.92	254569000	521246

Table 5.14
TFOT and RTFOT Effects on the Schwyer Rheometer Test

ASPHALT			OVEN TEMPERATURE		
			285°F Nj	325°F Nj	365°F Nj
MA30	TFOT	77°F	1.206E+06	2.243E+06	4.390E+06
MA30	TFOT	59°F	2.122E+07	2.620E+07	5.240E+07
MA30	RTFOT	77°F	2.836E+06	3.729E+06	3.218E+06
MA30	RTFOT	59°F	4.069E+07	4.780E+07	7.040E+07
BF30	TFOT	77°F	1.135E+06	2.069E+06	6.168E+06
BF30	TFOT	59°F	3.460E+07	4.523E+07	1.072E+08
BF30	RTFOT	77°F	1.526E+06	3.113E+06	6.523E+06
BF30	RTFOT	59°F	4.820E+07	8.612E+07	1.253E+08
MT30	TFOT	77°F	9.139E+05	1.871E+06	2.730E+06
MT30	TFOT	59°F	7.607E+07	5.210E+07	1.241E+08
MT30	RTFOT	77°F	1.419E+06	1.682E+06	2.679E+06
MT30	RTFOT	59°F	6.424E+07	5.830E+07	6.512E+07
BJ30A	TFOT	77°F	6.918E+05	2.693E+06	4.878E+06
BJ30A	TFOT	59°F	2.661E+07	9.145E+07	1.523E+08
BJ30A	RTFOT	77°F	7.384E+05	3.357E+06	4.740E+06
BJ30A	RTFOT	59°F	3.146E+07	6.007E+07	2.162E+08
CT30	TFOT	77°F	2.240E+06	2.622E+06	4.091E+06
CT30	TFOT	59°F	5.086E+07	8.103E+07	1.259E+08
CT30	RTFOT	77°F	2.699E+06	2.618E+06	4.282E+06
CT30	RTFOT	59°F	4.119E+07	6.083E+07	9.348E+07

Table 5.14 -- Continued

ASPHALT			OVEN TEMPERATURE		
			285°F Nj	325°F Nj	365°F Nj
MA20C	TFOT	77°F	6.044E+05	1.182E+06	3.107E+06
MA20C	TFOT	41°F	9.972E+08	8.493E+08	2.073E+09
MA20C	RTFOT	77°F	6.528E+05	6.850E+05	1.964E+06
MA20C	RTFOT	41°F	6.697E+08	1.256E+09	2.473E+09
MA20T	TFOT	77°F	2.562E+05	2.644E+05	6.999E+05
MA20T	TFOT	41°F	3.216E+08	7.226E+08	9.109E+08
MA20T	RTFOT	77°F	3.039E+05	6.675E+05	2.099E+06
MA20T	RTFOT	41°F	4.513E+08	5.146E+08	7.916E+08
MA20V	TFOT	77°F	5.049E+05	5.465E+05	1.250E+06
MA20V	TFOT	41°F	6.767E+08	8.064E+08	2.084E+09
MA20V	RTFOT	77°F	4.123E+05	6.310E+05	1.682E+06
MA20V	RTFOT	41°F	4.757E+08	6.813E+08	2.054E+09
TL20	TFOT	77°F	1.737E+06	2.860E+06	6.806E+06
TL20	TFOT	41°F	1.133E+09	2.715E+09	7.570E+09
TL20	RTFOT	77°F	2.267E+06	2.776E+06	8.567E+06
TL20	RTFOT	41°F	2.123E+09	4.203E+09	5.028E+09

Table 5.15 ANOVA on the Rheometer Test Results

41°F SOURCE	DF	ANOVA SS	F VALUE	PR >F
ASPHALT	3	3.587895479527E+19	17.76	0.0022
OVEN	1	8.045031317606E+14	0.00	0.9735
TEMP	2	1.710756580212E+19	12.71	0.0070
ASPHALT*OVEN	3	6.586750236695E+16	0.03	0.9913
ASPHALT*TEMP	6	1.034365879240E+19	2.56	0.1387
OVEN*TEMP	2	1.004507498132E+18	0.75	0.5136

59°F SOURCE	DF	ANOVA SS	F VALUE	PR >F
ASPHALT	4	8678182209014668.0	4.58	0.0322
OVEN	1	59330671960336.0	0.13	0.7325
TEMP	2	26348574128073500.0	27.83	0.0002
ASPHALT*OVEN	4	2976281389387996.0	1.57	0.2714
ASPHALT*TEMP	8	11600818804872336.0	3.06	0.0670
OVEN*TEMP	2	4348036038164.0	0.00	0.9954

77°F SOURCE	DF	ANOVA SS	F VALUE	PR >F
ASPHALT	8	70490652640426.259	30.01	0.0001
OVEN	1	1216989513771.125	4.14	0.0587
TEMP	2	67283685634763.368	114.57	0.0001
ASPHALT*OVEN	8	1917444626002.031	0.82	0.5994
ASPHALT*TEMP	16	30612108812535.961	6.52	0.0003
OVEN*TEMP	2	107356391528.258	0.18	0.8346

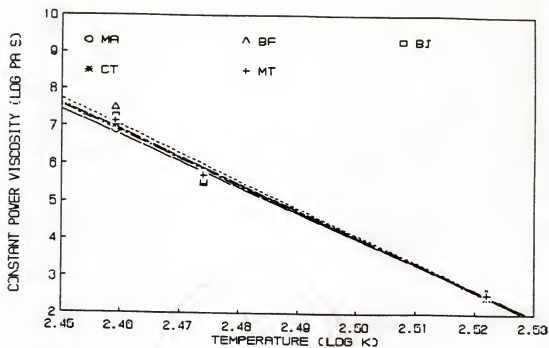


Figure 5.15 Constant Power Viscosity - Temperature (Original AC-30)

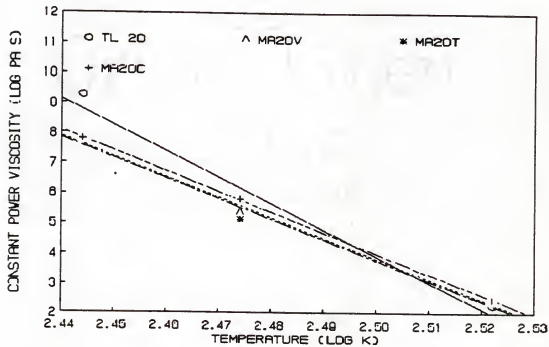


Figure 5.16 Constant Power Viscosity vs. Temperature (Original AC-20)

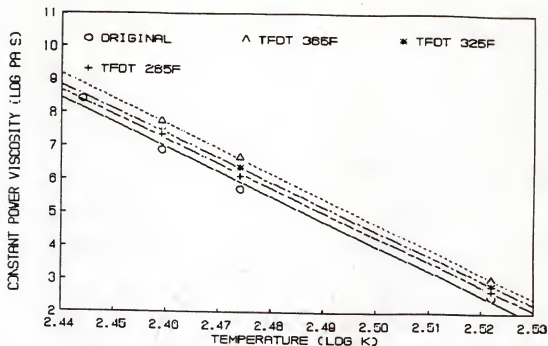


Figure 5.17 Constant Power Viscosity vs. Temperature (MA30)

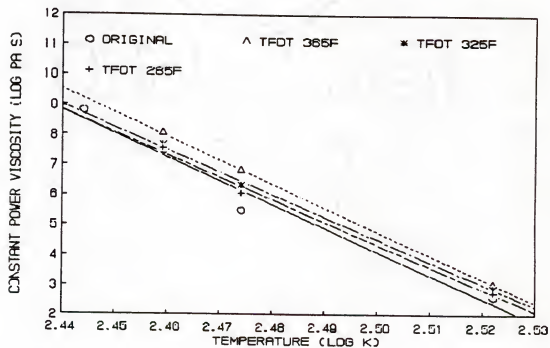


Figure 5.18 Constant Power Viscosity vs. Temperature (BF30)

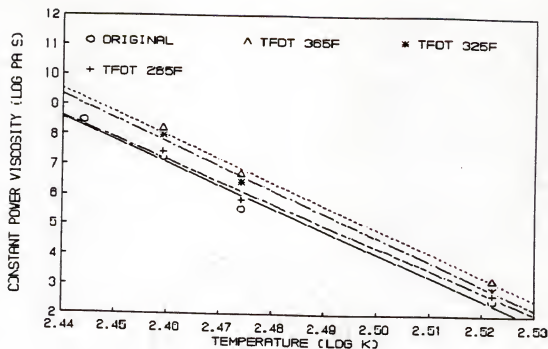


Figure 5.19 Constant Power Viscosity vs. Temperature (BJ30)

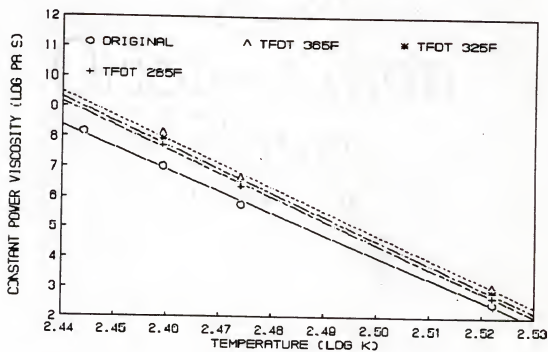


Figure 5.20 Constant Power Viscosity vs. Temperature (CT30)

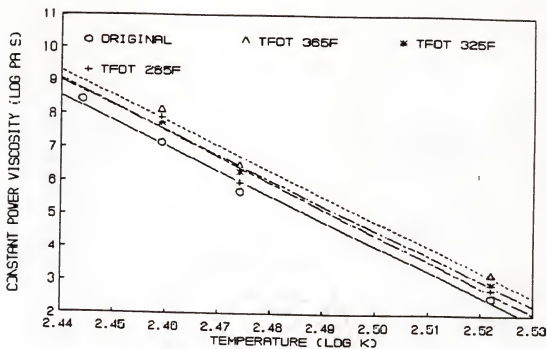


Figure 5.21 Constant Power Viscosity vs. Temperature (MT30)

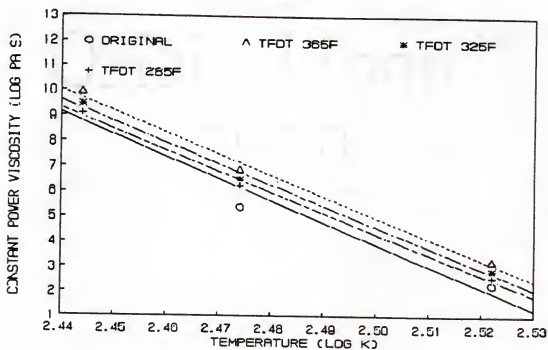


Figure 5.22 Constant Power Viscosity vs. Temperature (TL20)

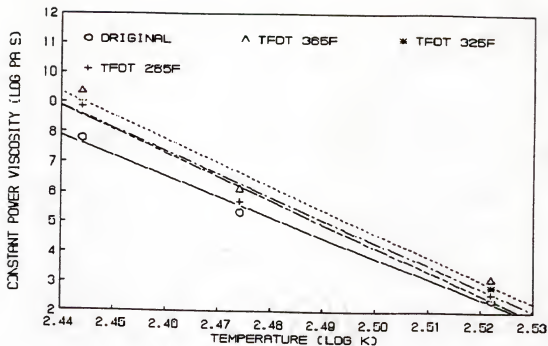


Figure 5.23 Constant Power Viscosity vs. Temperature (MA20V)

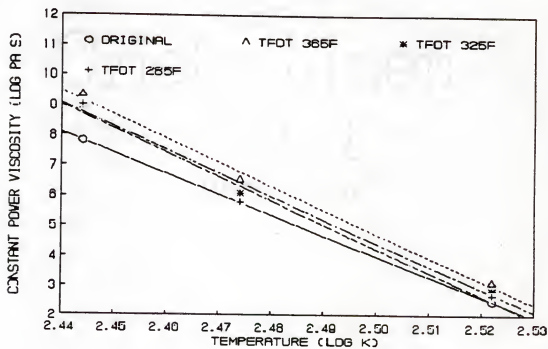


Figure 5.24 Constant Power Viscosity vs. Temperature (MA20C)

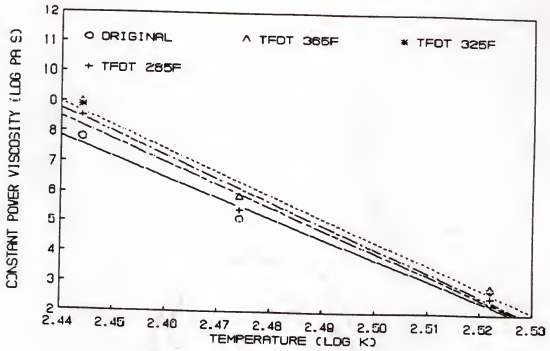


Figure 5.25 Constant Power Viscosity vs. Temperature (MA20T)

depends on the severity of the aging process since it shifts farther for higher oven temperature than that of lower oven temperature.

5.6 Summary of Findings

The major findings from the results of the tests on asphalt binders are summarized as follows:

1. On the basis of percent penetration retained and absolute viscosity ratio, the RTFOT is a more severe aging process than the TFOT for oven temperatures of 285 and 325 °F. However, the two processes are not significantly different from each other at an oven temperature of 365 °F.

2. The carbonyl ratio, which is a ratio of infrared absorbance at 1700 cm^{-1} and 1600 cm^{-1} , can be used to express the level of oxidation.

3. On the basis of carbonyl ratio, the effects of TFOT and RTFOT are not significantly different from each other at oven temperatures of 285 and 325 °F. But at 365 °F, the TFOT is a more severe aging process than the RTFOT from the stand point of carbonyl ratio.

4. On the basis of constant power viscosity, the effects of TFOT and RTFOT are not significantly different from each other at all three levels of temperature.

5. Asphalts of the same grade at high temperature (60 °C) can have very different properties at lower temperature.

6. Higher oven temperatures result in increased differentials in properties, i.e., the change in viscosity between 325 °F and 365 °F is greater than that between 285 °F and 325 °F.

7. The constant power viscosity - temperature relationship of asphalt is shifted parallel to the original relationship after aging

process. The relationship shifts farther for higher oven temperature than that of lower oven temperature.

CHAPTER 6 TESTS ON ASPHALT MIXTURES

6.1 Introduction

Of the twenty asphalts evaluated in the asphalt cement tests, five asphalts were used in a laboratory testing program to establish a relationship between mixture properties and the binder properties. Figure 1.3 shows the testing program of the asphalt mixtures. Each of these five asphalts was used to make Florida S-1 asphalt concrete mixtures, and Marshall specimens were fabricated from these mixtures. The compacted asphalt mix specimens were subjected to the following aging conditions:

- a. Aging in convectional oven at 140° F for 14, 28, and 90 days.
- b. Aging in forced-draft oven at 140° F for 14, 28, and 90 days.
- c. Aging in ultraviolet oven at 140° F for 14, 28, and 90 days.
- d. Aging under natural sunlight for 3, 6, 12, 24, and 48 months.
- e. No aging.

Four replicate specimens were made for each condition. The following tests were performed on the Marshall specimens at the various aging conditions:

- a. Resilient modulus tests at 41°, and 77° F
- b. Indirect tensile test at 41° F
- c. Indirect tensile test at 77° F.

After the specimens were broken in the indirect tensile tests, asphalt residues were recovered from the asphalt mixtures, and the

following tests were performed on the recovered asphalt residues and the original asphalts:

- a. Penetration at 77° F
- b. Absolute viscosity at 140° F
- c. IR spectral analysis
- d. Schweyer rheometer test at 59°, and 77° F
- e. Spot test.

6.1.1 Statistical Model for Asphalt Mixture Tests

The test results for asphalt mixtures were analyzed as results of a factorial experiment comprised of five asphalt (ASPHALT), three conditions of exposure (EXPOSURE), and four levels of duration of exposure (DURATION). ASPHALT, EXPOSURE, and DURATION were regarded as fixed effects. The following linear model was assumed for any single measurement in the experiment:

$$Y_{ijkl} = m + A_i + B_j + C_k + (AB)_{ij} + (AC)_{ik} + (BC)_{jk} + (ABC)_{ijk} + \epsilon_{ijkl}$$

where

Y_{ijkl} = the response of the l th replicate on the i th asphalt, j th exposure condition, and k th exposure duration

m = the overall mean

A_i = the main effect of i th asphalt

B_j = the main effect of j th exposure condition

C_k = the main effect of k th exposure duration

AB_{ij} = the interaction of i th asphalt x j th exposure condition

AC_{ik} = the interaction of i th asphalt x k th exposure duration

BC_{jk} = the interaction of j th exposure condition x k th exposure duration

ABC_{ijk} = the interaction of i th asphalt, j th exposure condition, and k th exposure duration

ϵ_{ijkl} = the experimental error.

6.2 Indirect Tensile Test on the Asphalt Mixtures

Results of the Indirect Tensile Test by asphalt, type of exposure and duration of exposure are tabulated in Appendix B.1. Results of ANOVA at different temperature are summarized in Table 6.1. At temperature of 41° F, all three main effects and interaction effects except ASPHALT*EXPOSURE are significant. For test at 77° F, all three main effects and EXPOSURE*DURATION are significant.

Since the primary concern was the long-term aging effect, the 90 days duration were subjected to a detailed study. Comparisons of means for EXPOSURE at 90 days duration were performed using Duncan's test at a level of significance of 0.05. The results are summarized in Table 6.2. At 77° F, the OVEN and FD give higher indirect tensile strength than does the UV. But at 41° F, the indirect tensile strength of the asphalt mixtures is close to the upper limit, therefore it is not appropriate to compare the exposure effect using the data at 41° F.

Figure 6.1 through 6.5 show the indirect tensile strength vs. log aging time in days for each asphalt. From the figures, the indirect tensile strength at 41° F is not affected much by the aging process since it is close the upper limit. At 77° F, the tensile strength

Table 6.1 ANOVA on Indirect Tensile Strength Test

41°F SOURCE	DF	ANOVA SS	F VALUE	PR > F
ASPHALT	4	14088.59495500	7.54	0.0001
EXPOSURE	2	7912.62162667	8.47	0.0004
DURATION	3	21257.31738667	15.18	0.0001
ASPHALT*EXPOSURE	8	5063.21141500	1.36	0.2281
ASPHALT*DURATION	12	20834.48450500	3.72	0.0002
EXPOSURE*DURATION	6	19100.65525333	6.82	0.0001

77°F SOURCE	DF	ANOVA SS	F VALUE	PR > F
ASPHALT	4	25919.53758333	92.13	0.0001
EXPOSURE	2	1633.25181500	11.61	0.0001
DURATION	3	89640.82745667	424.82	0.0
ASPHALT*EXPOSURE	8	514.02020167	0.91	0.5095
ASPHALT*DURATION	12	562.53187667	0.67	0.7785
EXPOSURE*DURATION	6	7918.50653833	18.76	0.0001

Table 6.2 Comparison on Exposure Effect for Tensile Strength

TEMPERATURE	DUNCAN GROUPING	MEAN(psi)	N	TYPE
41°F	A	436.72	10	UV
	A	430.53	10	FD
	B	374.10	10	OV
77°F	A	242.50	10	OV
	A	233.80	10	FD
	B	215.61	10	UV

*Means with the same letter are not significantly different.

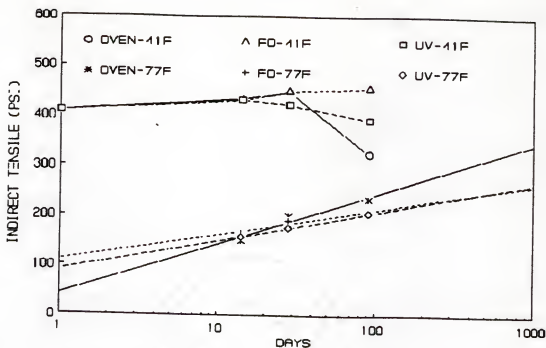


Figure 6.1 Indirect Tensile Strength vs. Time (MA)

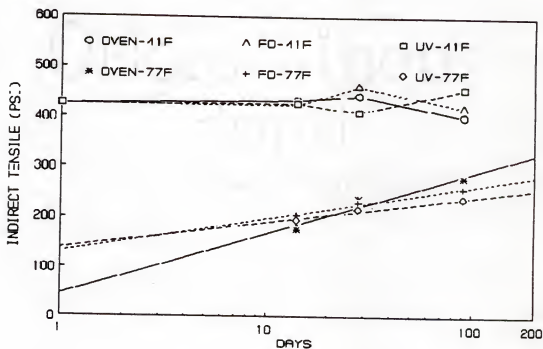


Figure 6.2 Indirect Tensile Strength vs. Time (BF)

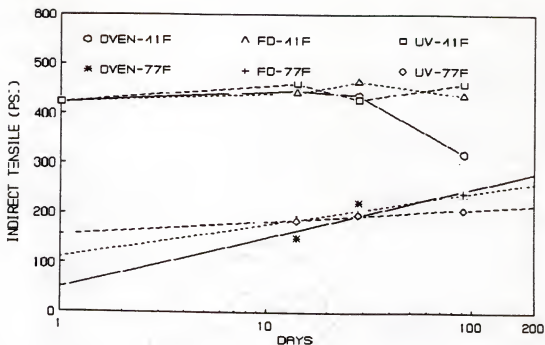


Figure 6.3 Indirect Tensile Strength vs. Time (BJ)

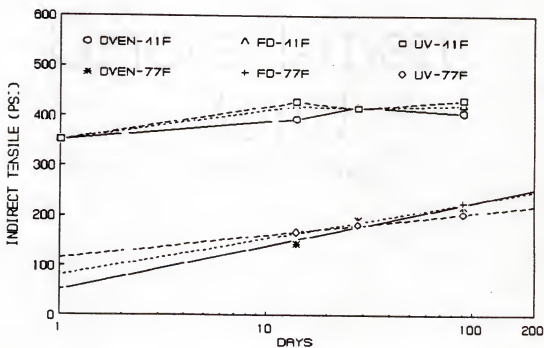


Figure 6.4 Indirect Tensile Strength vs. Time (CT)

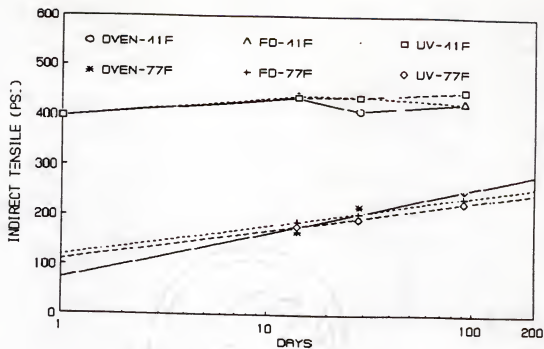


Figure 6.5 Indirect Tensile Strength vs. Time (MT)

increases with aging. It can be seen that there is a linear relationship between the indirect tensile strength at 77° F and log time in days. The OVEN gives the highest increasing rate of the indirect tensile strength while the UV gives the lowest increasing rate.

6.3 Resilient Modulus Test on the Asphalt Mixtures

Results of the Resilient Modulus Test are tabulated in Appendix

B.2. Results of ANOVA on the resilient moduli (both instantaneous, MRI, and total, MRT, recoveries are presented in Table 6.3.

At 77° F, the EXPOSURE effect is not significant for both MRI and MRT. At 41° F, the EXPOSURE effect was compared at duration of 90 days since the long-term aging effect was the major concern. It was found that the exposure types were not significant different for both MRI and MRT.

Figures 6.6 through 6.10 show the resilient moduli of mixtures vs. log time in days for each asphalt. The asphalt mixtures are so hard at 41° F that the total recoverable deformations are almost the same with the instantaneous recoverable deformations. Therefore the total resilient moduli are basically the same with the instantaneous resilient moduli for test at 41° F. It is found that the resilient moduli are either not changing much or even decreasing with age at 41° F. At 77° F, both the total and instantaneous resilient moduli increase with age. When the mixtures become harder with age, the difference between total resilient and instantaneous moduli gets smaller.

Table 6.3 ANOVA on Resilient Modulus

RMI 41°F SOURCE	DF	ANOVA SS	F VALUE	PR > F
ASPHALT	4	2950223256.888	1.07	0.3788
EXPOSURE	2	5174638952.515	3.74	0.0279
DURATION	3	11958545189.021	5.76	0.0012
ASPHALT*EXPOSURE	8	5620062654.900	1.01	0.4313
ASPHALT*DURATION	12	12516868833.140	1.51	0.1379
EXPOSURE*DURATION	6	20209431159.664	4.87	0.0003

RMI 77°F SOURCE	DF	ANOVA SS	F VALUE	PR > F
ASPHALT	4	3856568312.617	3.19	0.0172
EXPOSURE	2	72746070.998	0.12	0.8868
DURATION	3	25284883213.203	27.89	0.0001
ASPHALT*EXPOSURE	8	3800759639.136	1.57	0.1455
ASPHALT*DURATION	12	6048846046.420	1.67	0.0888
EXPOSURE*DURATION	6	3463064828.348	1.91	0.0086

RMT 41°F SOURCE	DF	ANOVA SS	F VALUE	PR > F
ASPHALT	4	3250633143.066	1.18	0.3234
EXPOSURE	2	5694771625.176	4.15	0.0191
DURATION	3	11813902354.335	5.74	0.0013
ASPHALT*EXPOSURE	8	5705676452.663	1.04	0.4132
ASPHALT*DURATION	12	12480341305.127	1.52	0.1344
EXPOSURE*DURATION	6	20240518347.682	4.92	0.0002

RMT 77°F SOURCE	DF	ANOVA SS	F VALUE	PR > F
ASPHALT	4	3235854276.014	3.38	0.0130
EXPOSURE	2	355993809.723	0.74	0.4788
DURATION	3	50024852224.604	69.59	0.0001
ASPHALT*EXPOSURE	8	4514017248.341	2.35	0.0245
ASPHALT*DURATION	12	5269255335.771	1.83	0.0556
EXPOSURE*DURATION	6	4993148364.262	3.47	0.0041

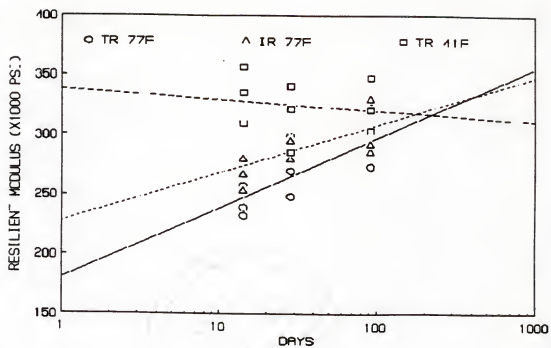


Figure 6.6 Resilient Modulus vs. Time (MA)

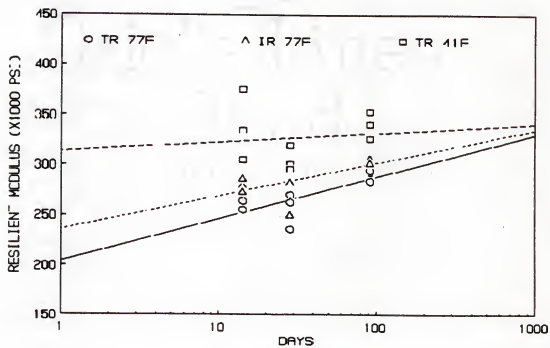


Figure 6.7 Resilient Modulus vs. Time (BF)

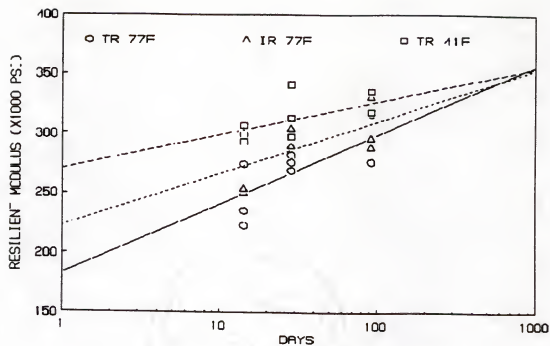


Figure 6.8 Resilient Modulus vs. Time (BJ)

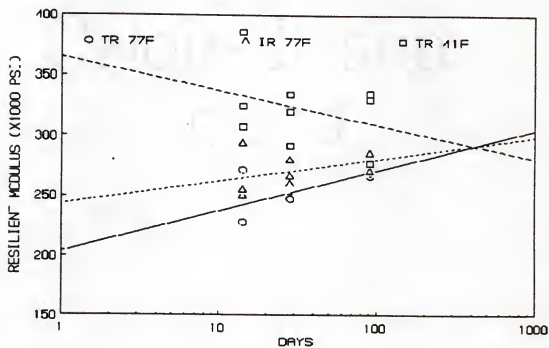


Figure 6.9 Resilient Modulus vs. Time (CT)

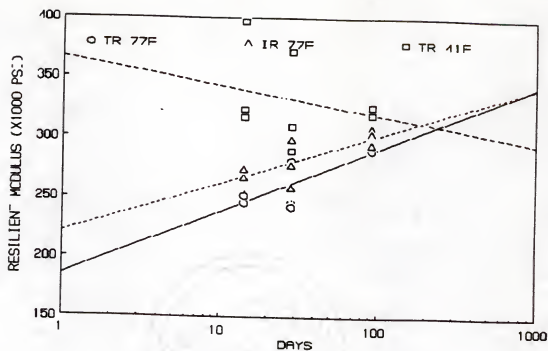


Figure 6.10 Resilient Modulus vs. Time (MT)

6.4 Fracture Energy Test on the Asphalt Mixtures

Results of the fracture energy are tabulated in Appendix B.3. Results of ANOVA on fracture energy at different temperature are presented in Table 6.4.

Comparisons on the exposure effect at duration of 90 days were performed. The results are summarized in Table 6.5. At 41° F, the UV and FD aging processes give higher fracture energy values than does OVEN. At 77° F, there is no different between the exposure types from the stand point of fracture energy.

Figures 6.11 through 6.15 show the fracture energy vs. log time in days for each asphalt. It is seen that the fracture energy decreases with time at 41° F, while the fracture energy increases with time at 77° F.

6.5 Penetration Test on Recovered Asphalts

The results of the penetration test on the recovered asphalts are shown in Table 6.6. Table 6.7 shows the results of ANOVA on the percent penetration retained. From Table 6.7, it is seen that all three main effects and the interaction effects except ASPHALT*EXPOSURE are significant.

Since the EXPOSURE interacts with DURATION, comparison on exposure effect must be done at each level of duration. However, the effects produced by long-term aging is the primary interest, therefore the comparison was done only on the duration of 90 days. This was performed using Duncan's test at a level of significance of 0.05. The results are summarized in Table 6.8. It is seen that the OVEN aging process is more severe than the UV and FD aging processes since the OVEN gives lower

Table 6.4 ANOVA on Fracture Energy

41°F SOURCE	DF	ANOVA SS	F VALUE	PR > F
ASPHALT	4	3425947.357	1.85	0.1273
EXPOSURE	2	14436934.968	15.57	0.0001
DURATION	3	6857564.143	4.93	0.0033
ASPHALT*EXPOSURE	8	4177727.402	1.13	0.3541
ASPHALT*DURATION	12	10677688.096	1.92	0.0432
EXPOSURE*DURATION	6	10415602.563	3.75	0.0024

77°F SOURCE	DF	ANOVA SS	F VALUE	PR > F
ASPHALT	4	14575014.734	21.90	0.0001
EXPOSURE	2	2460871.689	7.40	0.0011
DURATION	3	9671087.483	19.38	0.0001
ASPHALT*EXPOSURE	8	1322253.430	0.99	0.4472
ASPHALT*DURATION	12	2117909.015	1.06	0.4032
EXPOSURE*DURATION	6	9588970.851	9.61	0.0001

Table 6.5 Comparison on Exposure Effect for Fracture Energy

TEMPERATURE	DUNCAN GROUPING	MEAN	N	EXPOSURE
41°F	A	4366.5	10	UV
	A	4215.6	10	FD
	B	3148.1	10	OV
77°F	A	3765.4	10	FD
	A	3758.2	10	OV
	A	3429.6	10	UV

*Means with the same letter are not significantly different.

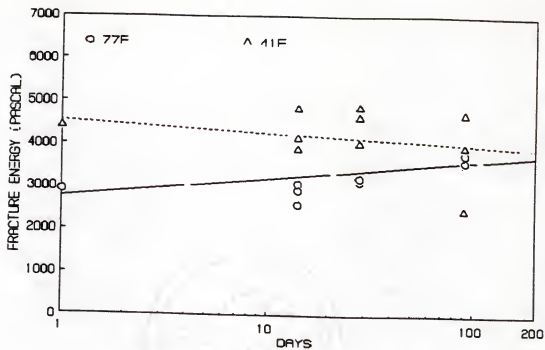


Figure 6.11 Fracture Energy vs. Time (MA)

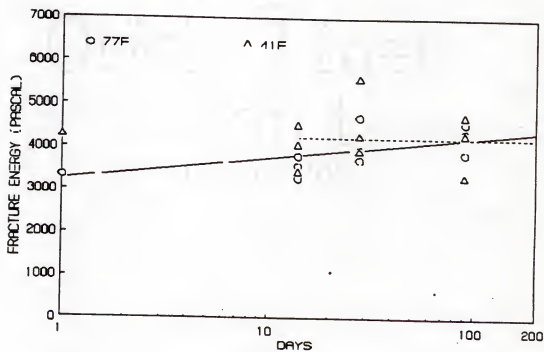


Figure 6.12 Fracture Energy vs. Time (BF)

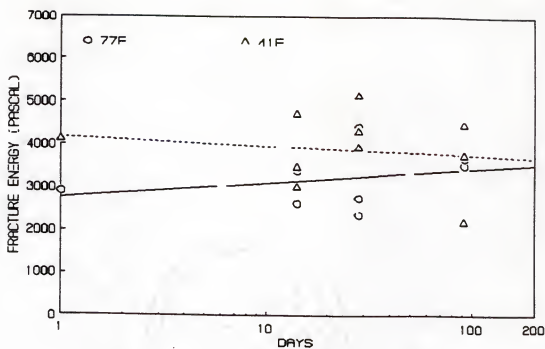


Figure 6.13 Fracture Energy vs. Time (BJ)

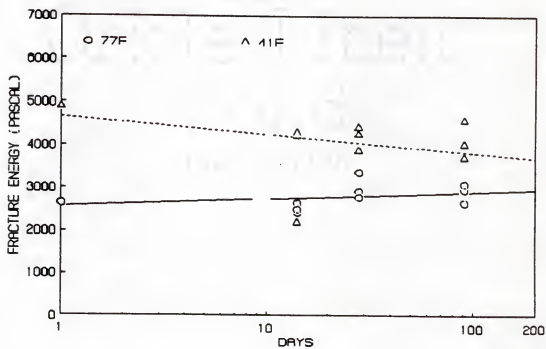


Figure 6.14 Fracture Energy vs. Time (CT)

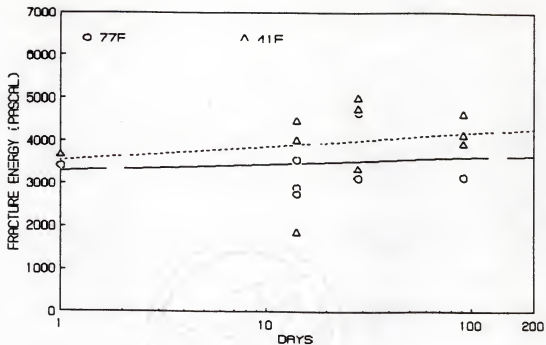


Figure 6.15 Fracture Energy vs. Time (MT)

Table 6.6 Results of Penetration Tests

	TYPE	MA	BF	BJ	CT	MT
0 DAY	--	41	37	32	36	31
14 DAYS	OV	34	30	30	33	26
	UV	34	32	28	33	29
	FD	31	29	27	33	31
28 DAYS	OV	31	25	26	28	25
	UV	33	27	27	32	27
	FD	33	27	28	34	28
90 DAYS	OV	24	19	22	19	20
	UV	25	20	22	24	21
	FD	27	23	20	25	23
3 MONTH	NATURAL	34	32	30	31	26
6 MONTH	NATURAL	30	24	28	30	26

Table 6.7 ANOVA on Penetration Test for Recovered Asphalts

SOURCE	DF	ANOVA SS	F VALUE	PR > F
ASPHALT	4	722.540	42.52	0.0001
EXPOSURE	2	68.005	8.00	0.0022
DURATION	3	4057.342	318.39	0.0001
ASPHALT*EXPOSURE	8	66.063	1.94	0.0994
ASPHALT*DURATION	12	265.978	5.22	0.0003
EXPOSURE*DURATION	6	77.281	3.03	0.0237

Table 6.8 Comparison of the Exposure Effect on Penetration
Retained for Recovered Asphalts

DUNCAN GROUPING	MEAN	N	EXPOSURE
A	41.226	5	FD
A B	39.028	5	UV
B	36.206	5	OV

*Means with the same letter are not significantly different.

penetration values. Figures 6.16 through 6.20 show the penetration vs. log time in days for each asphalt.

6.6 Absolute Viscosity Test on the Recovered Asphalts

The results of the absolute viscosity tests are shown in Table 6.9. Results of ANOVA on the absolute viscosity ratio are summarized in Table 6.10. From Table 6.10, it is seen that all three main effects and the interaction effects except ASPHALT*EXPOSURE are significant.

Since the EXPOSURE interacts with DURATION, comparison exposure effect must be done at each level of durations. The duration of 90 days was chosen for comparison because the long-term effects were the primary concern. This was performed using Duncan's test at a level of significance of 0.05. The results are summarized in Table 6.11. From Table 6.11, it is seen that the OVEN aging process is more severe than the FD and UV aging processes.

Figures 6.21 through 6.25 show the absolute viscosity vs. log time in days for each asphalt.

6.7 IR Spectroscopy on the Recovered Asphalts

The results of the infrared spectroscopy are shown in Table 6.12. Results of ANOVA are summarized in Table 6.13. From Table 6.13, it is seen that all three main effects and the interaction effects except ASPHALT*EXPOSURE are significant.

Comparison on the exposure effect was done at different level of durations. Table 6.14 shows the comparison on the exposure effect at duration of 90 days. It is seen that OVEN and FD are more severe aging

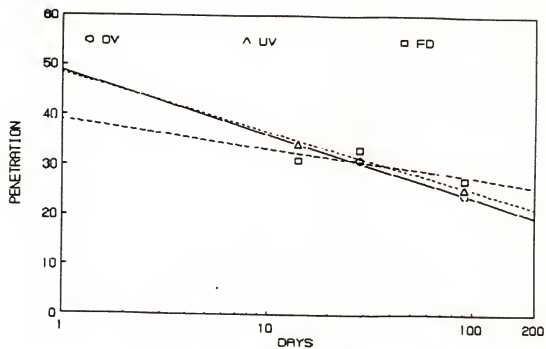


Figure 6.16 Penetration vs. Time (MA)

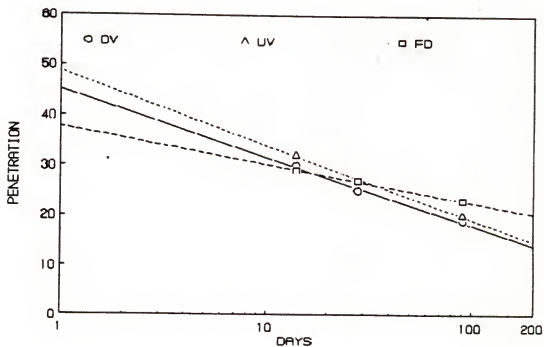


Figure 6.17 Penetration vs. Time (BF)

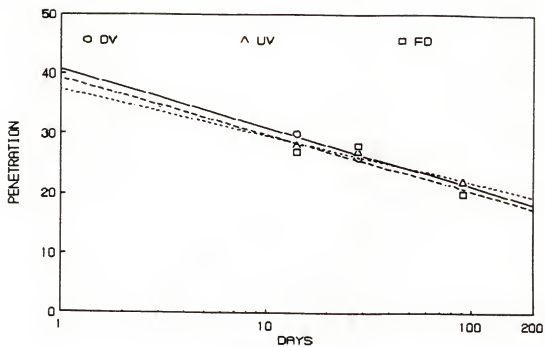


Figure 6.18 Penetration vs. Time (BJ)

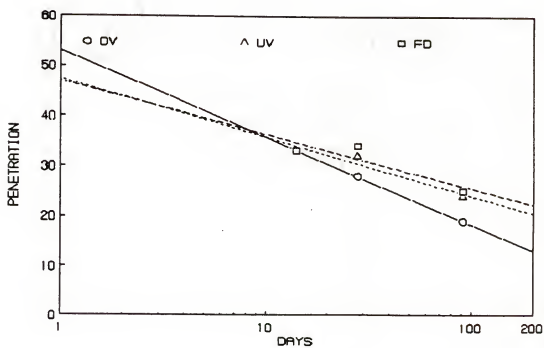


Figure 6.19 Penetration vs. Time (CT)

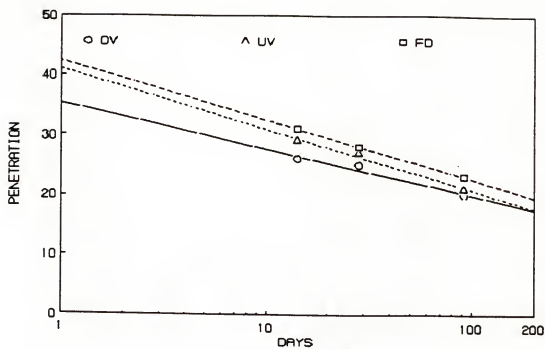


Figure 6.20 Penetration vs. Time (MT)

Table 6.9 Results of Absolute Viscosity

	TYPE	MA	BF	BJ	CT	MT
0 DAY	--	6491	7010	10777	10567	9424
14 DAYS	OV	9297	11487	16991	19497	15803
	UV	9845	10430	16076	15637	12699
	FD	10818	11533	15341	14531	9910
28 DAYS	OV	11443	16360	27873	27130	25236
	UV	11529	14857	17384	19470	16176
	FD	11306	15328	17444	17598	17256
90 DAYS	OV	34710	41446	49087	64973	56289
	UV	21372	28690	31502	42216	35844
	FD	18651	23048	43330	49245	31051
3 MONTH	NATURAL	10313	11310	14959	20239	20225
6 MONTH	NATURAL	14171	16074	20353	21931	22904

Table 6.10 ANOVA on Viscosity Ratio for the Recovered Asphalt

SOURCE	DF	ANOVA SS	F VALUE	PR > F
ASPHALT	4	187.369	69.37	0.0001
EXPOSURE	2	46.092	34.13	0.0001
DURATION	3	692.748	341.97	0.0001
ASPHALT*EXPOSURE	8	9.549	1.77	0.1337
ASPHALT*DURATION	12	92.732	11.44	0.0001
EXPOSURE*DURATION	6	51.215	12.64	0.0001

Table 6.11 Comparison of the Exposure Effect on Viscosity Ratio for Recovered Asphalts

DUNCAN GROUPING	MEAN	N	EXPOSURE
A	14.918	5	OV
B	10.108	5	FD
B	9.638	5	UV

*Means with the same letter are not significantly different.

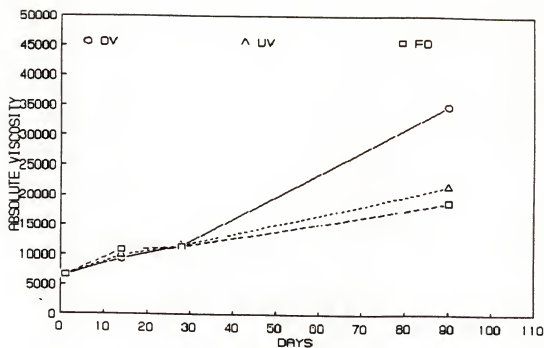


Figure 6.21 Absolute Viscosity vs. Time (MA)

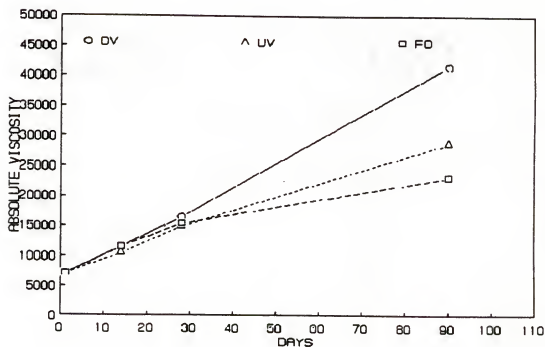


Figure 6.22 Absolute Viscosity vs. Time (BF)

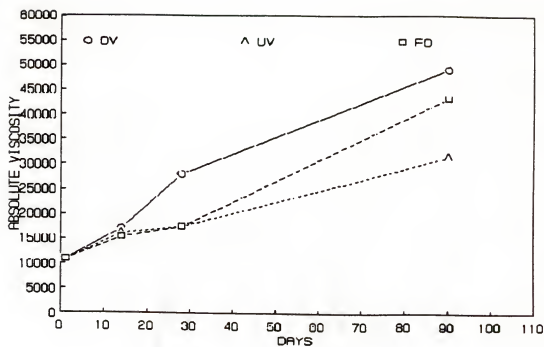


Figure 6.23 Absolute Viscosity vs. Time (BJ)

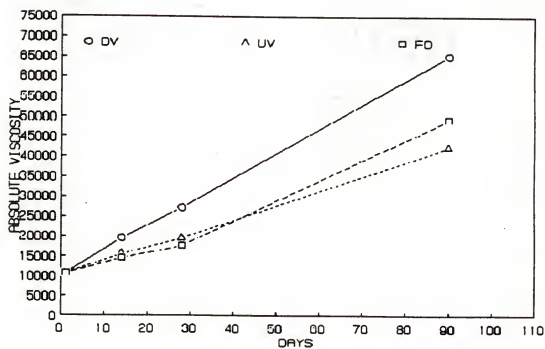


Figure 6.24 Absolute Viscosity vs. Time (CT)

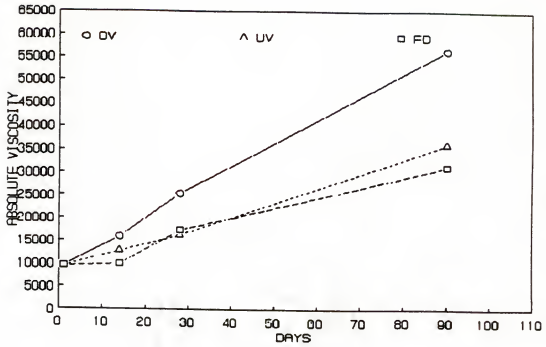


Figure 6.25 Absolute Viscosity vs. Time (MT)

Table 6.12 Results of the Infrared Spectroscopy on the Recovered Asphalts

ASPHALT	DURATION	OVEN	CARBONYL RATIO FD	UV
MA	ORIGINAL	0.3277		
MA	0 DAY	0.4053	0.4053	0.4053
MA	14 DAY	0.4744	0.4855	0.4457
MA	28 DAY	0.5233	0.5024	0.4785
MA	90 DAY	0.6406	0.6066	0.5648
BF	ORIGINAL	0.3673		
BF	0 DAY	0.4182	0.4182	0.4182
BF	14 DAY	0.4902	0.4896	0.4784
BF	28 DAY	0.5232	0.5383	0.4931
BF	90 DAY	0.6564	0.6683	0.5858
MT	ORIGINAL	0.3282		
MT	0 DAY	0.3818	0.3818	0.3818
MT	14 DAY	0.4556	0.4407	0.4279
MT	28 DAY	0.4883	0.5077	0.4681
MT	90 DAY	0.6171	0.5740	0.5459
BJ	ORIGINAL	0.3370		
BJ	0 DAY	0.3884	0.3884	0.3884
BJ	14 DAY	0.4559	0.4643	0.4554
BJ	28 DAY	0.5026	0.4927	0.4789
BJ	90 DAY	0.5875	0.6024	0.5338
CT	ORIGINAL	0.3584		
CT	0 DAY	0.3792	0.3792	0.3792
CT	14 DAY	0.4290	0.4400	0.4423
CT	28 DAY	0.5296	0.4980	0.4754
CT	90 DAY	0.6906	0.6354	0.5440

Table 6.13 ANOVA on Carbonyl Ratio for the Recovered Asphalts

SOURCE	DF	ANOVA SS	F VALUE	PR > F
ASPHALT	4	0.01322146	16.34	0.0001
EXPOSURE	2	0.01184001	29.26	0.0001
DURATION	3	0.34647034	570.90	0.0001
ASPHALT*EXPOSURE	8	0.00133524	0.83	0.5889
ASPHALT*DURATION	12	0.00542401	2.23	0.0452
EXPOSURE*DURATION	6	0.01105173	9.11	0.0001

Table 6.14 Comparison of Exposure Effect on Carbonyl Ratio
for Recovered Asphalts

DUNCAN GROUPING	MEAN	N	EXPOSURE
A	0.63844	5	OV
A	0.61734	5	FD
B	0.55486	5	UV

*Means with the same letter are not significantly different.

processes than UV. Figures 6.26 through 6.30 show the carbonyl ratio vs. log time in days for each asphalt.

6.8 Schweyer Rheometer Test on the Recovered Asphalts

The Schweyer rheometer test was performed on the recovered asphalts at 59° and 77° F. The results are shown in Appendix C. Results of ANOVA at different temperature are summarized in Table 6.15. For tests at temperature of 59° F, all three main effects and interaction effects are significant. For tests at 77° F, all three main effects and interaction effects except ASPHALT*EXPOSURE are significant.

Comparison on the exposure effect was performed on the results corresponding to the test temperature of 77° F. Table 6.16 shows the comparison to the exposure effect for duration of 90 days. It is seen that the OVEN is a more severe aging process than FD and UV from the stand point of Schweyer rheometer test.

Figures 6.31 through 6.35 show the constant power viscosity vs. log time in days for each asphalt. It can be seen that the hardening rates of the three aging processes are different since the slopes are different. And the hardening rates of each asphalt at both temperature (59° and 77° F) are about the same for each aging process. Figures 6.36 through 6.40 show the aging effect on the constant power viscosity vs. temperature relationships for each asphalt. It is seen that the asphalt constant power viscosity vs. temperature relationship is shifted almost parallel to the no aging relationship after aging. It shifts farther as the asphalt ages longer.

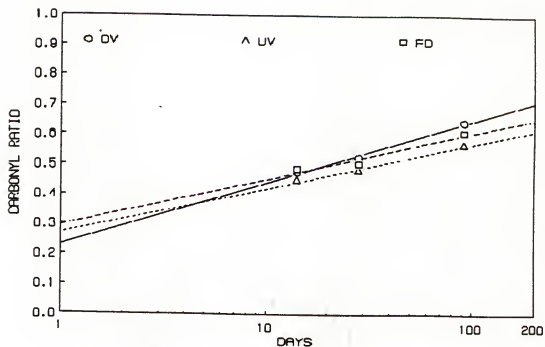


Figure 6.26 Carbonyl Ratio vs. Time (MA)

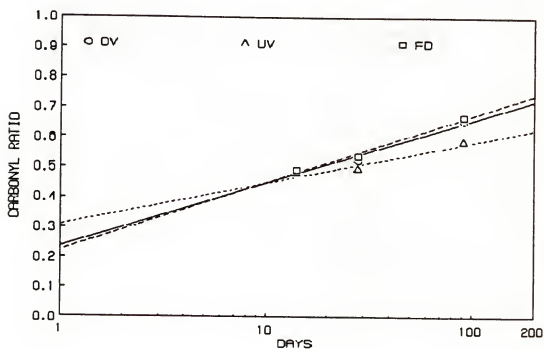


Figure 6.27 Carbonyl Ratio vs. Time (BF)

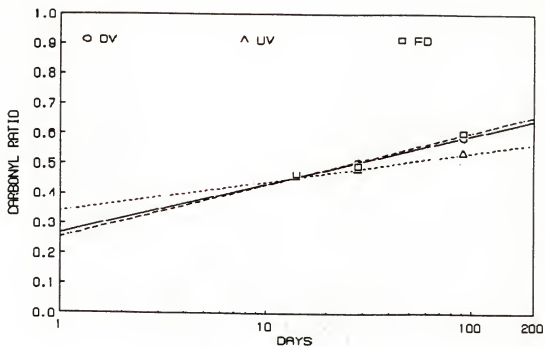


Figure 6.28 Carbonyl Ratio vs. Time (BJ)

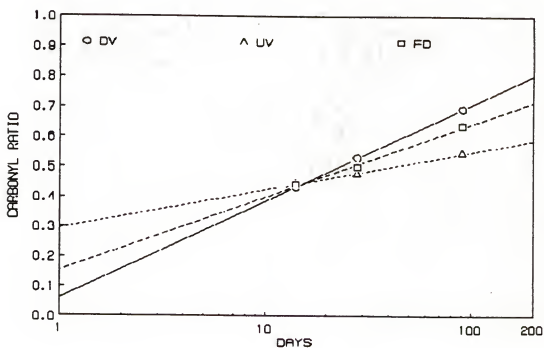


Figure 6.29 Carbonyl Ratio vs. Time (CT)

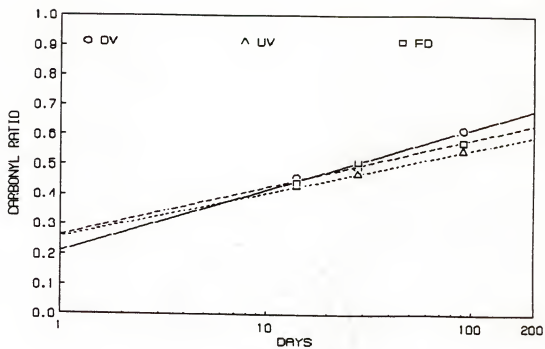


Figure 6.30 Carbonyl Ratio vs. Time (MT)

Table 6.15 ANOVA on Constant Power Viscosity for the Recovered Asphalt

59°F SOURCE	DF	ANOVA SS	F VALUE	PR > F
ASPHALT	4	7.654E+16	9.35	0.0001
EXPOSURE	2	1.740E+16	4.25	0.0174
DURATION	3	3.178E+17	51.77	0.0001
ASPHALT*EXPOSURE	8	4.851E+16	2.96	0.0057
ASPHALT*DURATION	12	1.208E+17	4.92	0.0001
EXPOSURE*DURATION	6	1.017E+17	8.29	0.0001

77°F SOURCE	DF	ANOVA SS	F VALUE	PR > F
ASPHALT	4	2.522E+14	6.35	0.0002
EXPOSURE	2	2.711E+14	13.65	0.0001
DURATION	3	1.594E+15	53.53	0.0001
ASPHALT*EXPOSURE	8	1.089E+14	1.37	0.2209
ASPHALT*DURATION	12	2.529E+14	2.12	0.0236
EXPOSURE*DURATION	6	5.627E+14	9.45	0.0001

Table 6.16 Comparison of Exposure Effect on Constant Power Viscosity
for Recovered Asphalts

TEMPERATURE	DUNCAN GROUPING	MEAN	N	EXPOSURE
59°F	A	266987720	10	OV
	B	156354940	10	FD
	B	124827280	10	UV
77°F	A	18256463	10	OV
	B	7606276	10	FD
	B	7168253	10	UV

*Means with the same letter are not significantly different.

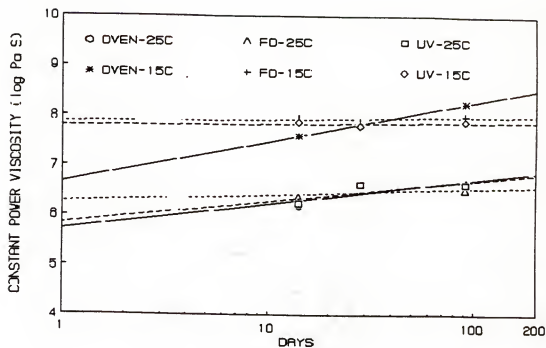


Figure 6.31 Constant Power Viscosity vs. Time (MA)

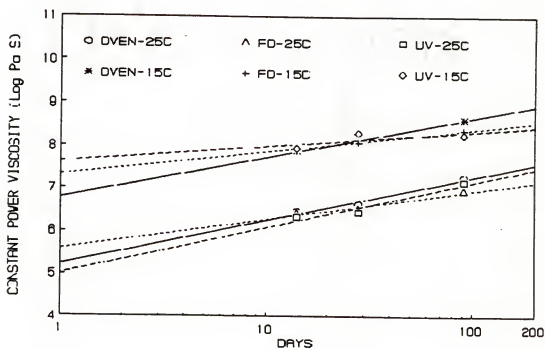


Figure 6.32 Constant Power Viscosity vs. Time (BF)

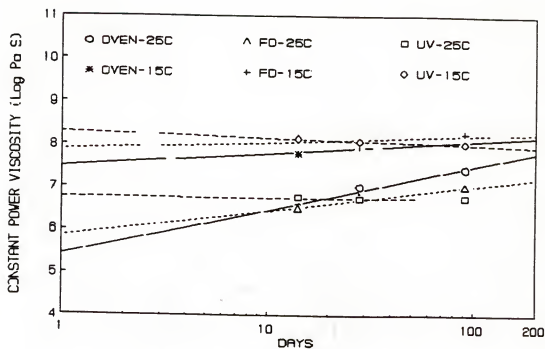


Figure 6.33 Constant Power Viscosity vs. Time (BJ)

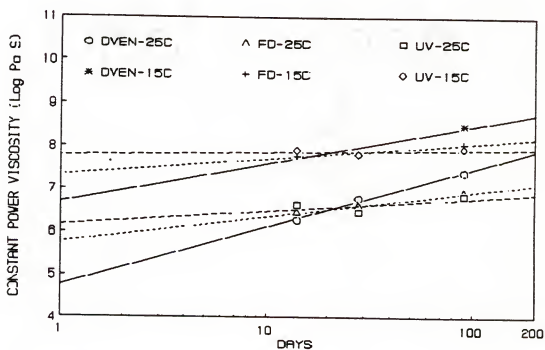


Figure 6.34 Constant Power Viscosity vs. Time (CT)

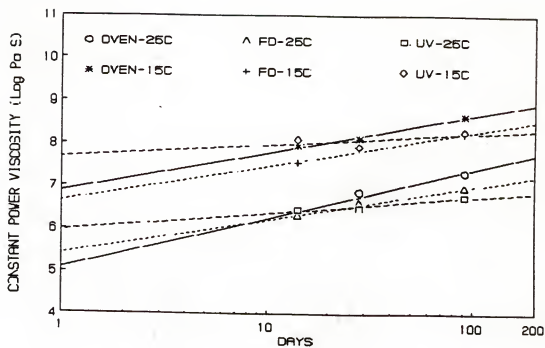


Figure 6.35 Constant Power Viscosity vs. Time (MT)

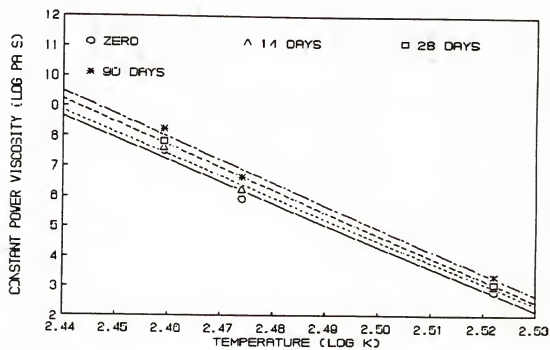


Figure 6.36 Constant Power Viscosity vs. Temperature (MA)

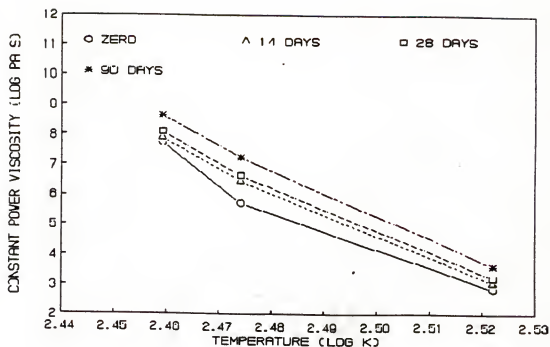


Figure 6.37 Constant Power Viscosity vs. Temperature (BF)

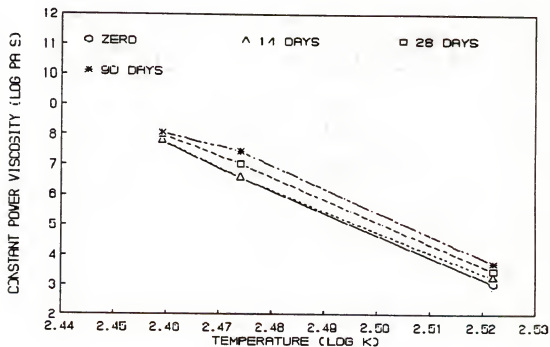


Figure 6.38 Constant Power Viscosity vs. Temperature (BJ)

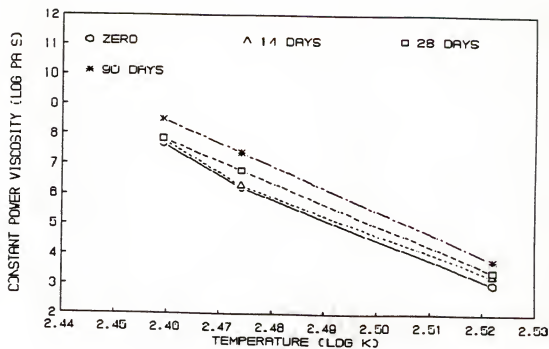


Figure 6.39 Constant Power Viscosity vs. Temperature (CT)

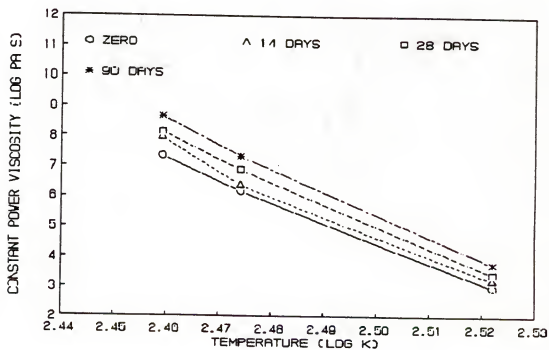


Figure 6.40 Constant Power Viscosity vs. Temperature (MT)

CHAPTER 7 TESTS ON THE FIELD SAMPLES

The field samples presented in this chapter include two groups. The first group is the Marshall specimens aged on the roof under natural weathering, and the other one is the core samples from three selected sections of asphalt concrete pavements in Hernando County in the state of Florida. The following tests were performed on the Marshall specimens and the core samples at the various aging time:

- a. Resilient modulus tests at 41, and 77 °F
- b. Indirect tensile test at 41 °F
- c. Indirect tensile test at 77 °F.

After the specimens were broken in the indirect tensile tests, asphalt residues were recovered from the asphalt mixtures, and the following tests were performed on the recovered asphalt residues and the original asphalts:

- a. Penetration at 77 °F
- b. Absolute viscosity at 140 °F
- c. IR spectral analysis
- d. Schweyer rheometer test at 59, and 77 °F

7.1 Marshall Specimens Under Natural Weathering

This section presents the test results of the Marshall specimens which were aged on the roof under natural sunlight. The results include two parts. One is the test results from the Marshall specimens made in

this research project, which were aged up to 12 months. The other is the test results from the Marshall specimens made in a previous research project, which were aged up to three years.

The aging condition and the tests performed on the specimens are described in Section 7.1. The results of indirect tensile test, resilient modulus test, and fracture energy are presented in Appendix D.

Figures 7.1 through 7.4 show the indirect tensile strength vs. time relationships for the specimens under natural weathering. From Figure 7.3, the indirect tensile strength at 41 °F drops after two years of aging. In Figure 7.4, the indirect tensile strength at 77 °F increases as specimens age. Most of the strength gaining occurs during the first year. After 2 years of aging, the indirect tensile strength at 77 °F is about the same for each type of asphalt mixture. The indirect tensile strength of ES and TA is much different from others at 77 °F since the ES is a roofing asphalt and TA is a airblown asphalt. However, the difference is not that much at 41 °F.

Figures 7.5 through 7.8 show the total resilient modulus vs. aging time for the specimens under natural weathering. At 41 °F, the total resilient modulus does not change much during aging. At 77 °F, it increases during the first year of aging and then the rate of increase slows down.

Figures 7.9 through 7.12 show the fracture energy vs. aging time for the specimens under natural weathering. At 77 °F, the fracture energy does not show much difference except a little drop after 2 years of aging. At 41 °F, the fracture energy show a significant drop after 2 years of aging.

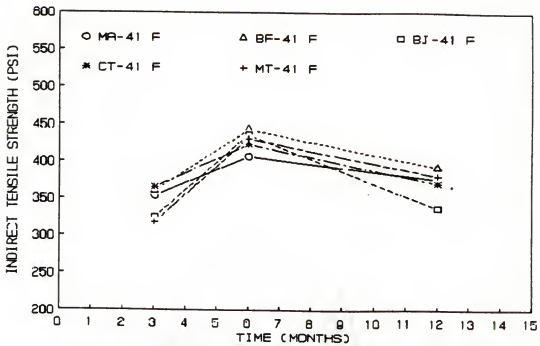


Figure 7.1 Indirect Tensile Strength at 41 °F vs. Time
(Natural Weathering Samples)

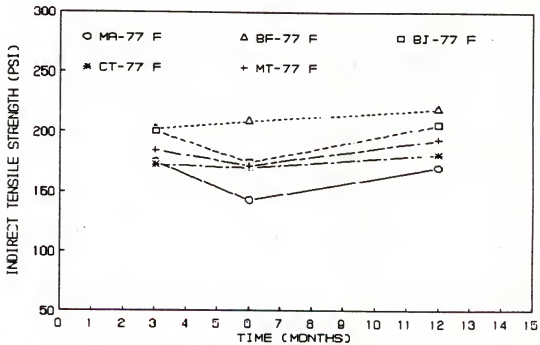


Figure 7.2 Indirect Tensile Strength at 77 °F vs. Time
(Natural Weathering Samples)

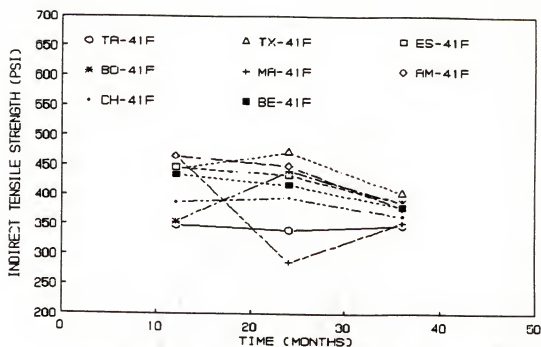


Figure 7.3 Indirect Tensile Strength at 41 °F vs. Time (Natural Weathering Samples from Previous Research)

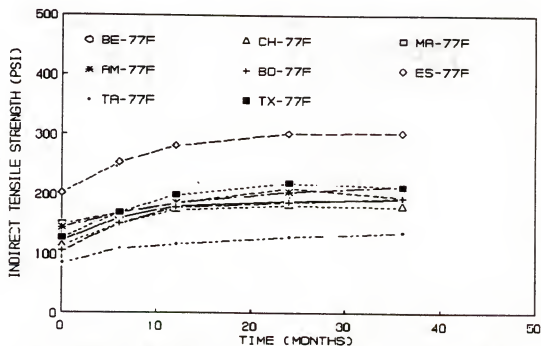


Figure 7.4 Indirect Tensile Strength at 77 °F vs. Time (Natural Weathering Samples from Previous Research)

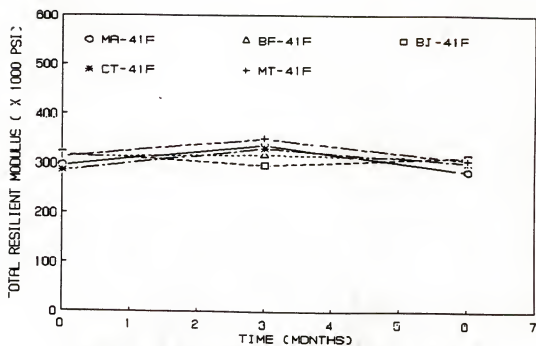


Figure 7.5 Total Resilient Modulus at 41 °F vs. Time
(Natural Weathering Samples)

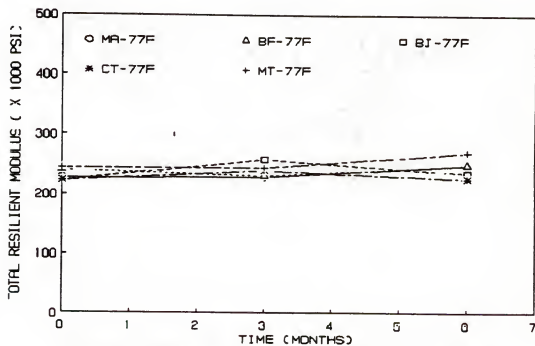


Figure 7.6 Total Resilient Modulus at 77 °F vs. Time
(Natural Weathering Samples)

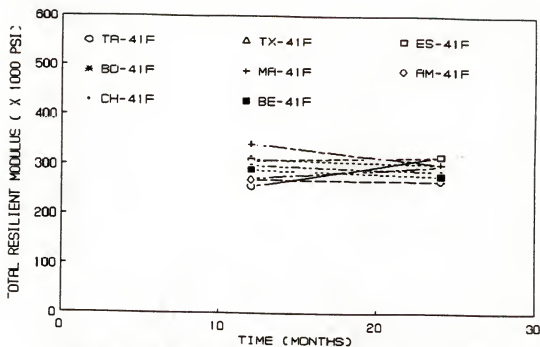


Figure 7.7 Total Resilient Modulus at 41 °F vs. Time
(Natural Weathering Samples from Previous Research)

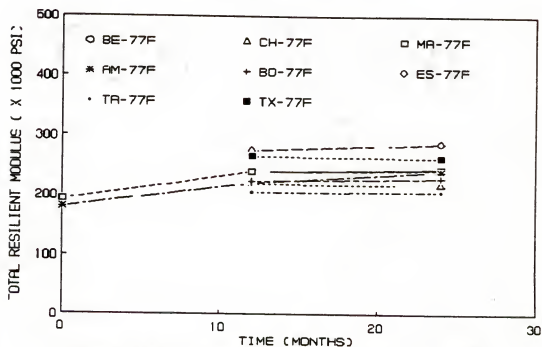


Figure 7.8 Total Resilient Modulus at 77 °F vs. Time
(Natural Weathering Samples from Previous Research)

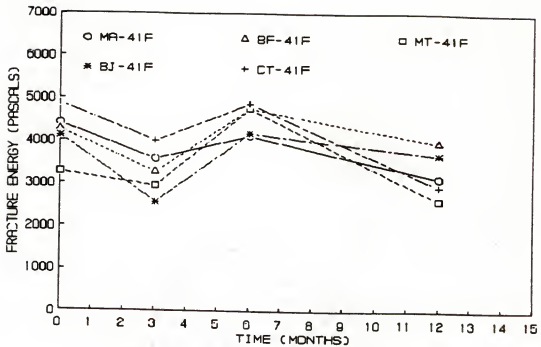


Figure 7.9 Fracture Energy at 41 °F vs. Time
(Natural Weathering Samples)

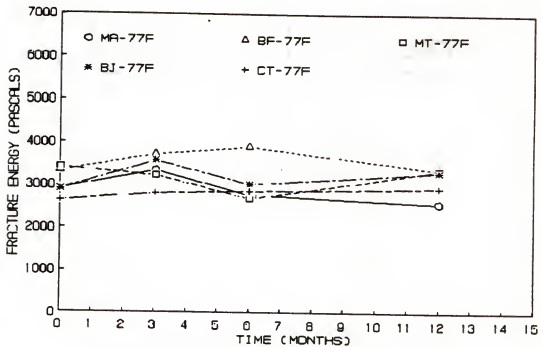


Figure 7.10 Fracture Energy at 77 °F vs. Time
(Natural Weathering Samples)

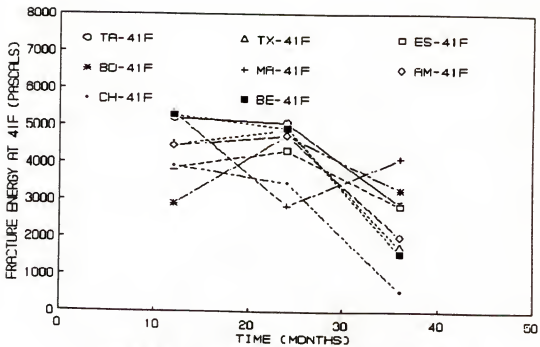


Figure 7.11 Fracture Energy at 41 °F vs. Time
(Natural Weathering Samples from Previous Research)

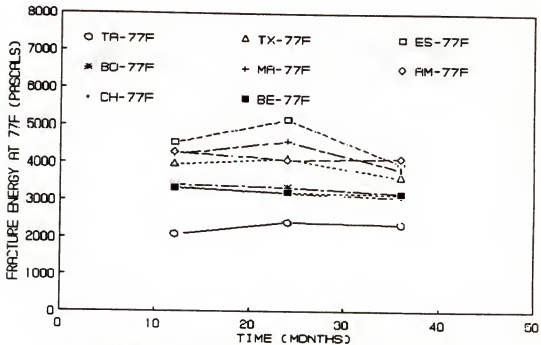


Figure 7.12 Fracture Energy at 77 °F vs. Time
(Natural Weathering Samples from Previous Research)

The test results of penetration, absolute viscosity, and FTIR test for the specimens under natural weathering are shown in the Tables 7.1 through 7.3. Figures 7.13 through 7.18 show the penetration, absolute viscosity, and carbonyl ratio vs. time of aging. It is seen that most of the change of penetration value occurs during the first year of aging. The difference is not that much after 1 year of aging. From Figure 7.16, the absolute viscosity increases during the first six months, after six months the absolute viscosity increases at lower rate. For carbonyl ratio, it increases rapidly during the first 6 month, it does not change much after 1 year. It is found that the carbonyl ratio has a linear relationship with time in log days. Figures 7.19 and 7.20 show the carbonyl ratio vs. time in log days relationship.

Tables 7.4 and 7.5 show the results of Schweyer rheometer test on the recovered asphalts from the specimens under natural weathering. Figures 7.21 through 7.24 show the constant power viscosity vs. time of aging. From Figures 7.23 and 7.24, it is seen that the constant power viscosity increases rapidly during the first year of aging, after 1 year the increasing rate slows down. It is found that the constant power viscosity vs. log time has a linear relationship as shown in Figures 7.25 and 7.26.

Figures 7.27 through 7.31 show the constant power viscosity vs. temperature relationship. It is seen that the asphalt constant power viscosity - temperature relationship is shifted parallel to the no aging relationship after aging. The relationship shifts farther as the asphalt ages longer.

Table 7.1 Penetration Test Results

SPEC NO	ORIGINAL	NO AGING	3 MONTH NATURAL	6 MONTH NATURAL	1 YEAR NATURAL
MA	61	41	34	30	33
BF	55	37	32	24	30
BJ	61	32	30	28	26
CT	57	36	31	30	30
MT	53	31	26	26	33

SPEC NO	ORIGINAL NATURAL PENT.	NO AGING NATURAL PENT.	6 MONTH NATURAL PENT.	1 YEAR NATURAL PENT.	2 YEAR NATURAL PENT.	3 YEAR NATURAL PENT.
AM	73	48	34	29	27	26
BE	67	41	30	27	24	24
BO	76	49	32	36	33	30
CH	68	42	29	26	23	26
ES	27	22	17	16	15	17
MA	62	40	33	23	24	23
TA	82	42	53	47	45	44
TX	88	45	30	28	24	28

Table 7.2 Absolute Viscosity Test Results

SPEC NO	ORIGINAL NATURAL	NO AGING NATURAL	3 MONTH NATURAL	6 MONTH NATURAL	1 YEAR NATURAL
MA	3202	6491	10313	14171	14246
BF	4130	7010	11310	16074	13525
BJ	3335	10777	14959	20353	26346
CT	2890	10567	20239	21931	26589
MT	3410	9424	20225	22904	21446

Results of Absolute Viscosity Tests From Previous Research

SPEC NO.	ORIGINAL NATURAL	NO AGING NATURAL	6 MONTH NATURAL	1 YEAR NATURAL	2 YEAR NATURAL	3 YEAR NATURAL
AM	3301	7344	16008	24695	34930	37424
BE	2753	8906	21207	26340	38121	60959
BO	3810	11315	30860	20546	26792	44427
CH	3100	11322	32004	39178	54162	65981
ES	17885	34021	70574	83477	96941	97325
MA	2967	7096	9995	21977	23429	34059
TA	1931	2392	4162	5413	7010	7910
TX	1064	2345	4536	5288	6673	7335

Table 7.3 FTIR Test Results

SPEC	ORIGINAL	NO AGING	3 MONTH	6 MONTH	1 YEAR
MA	0.3277	0.4053	0.4979	0.5140	0.5247
BF	0.3673	0.4182	0.5027	0.5333	0.5406
BJ	0.3370	0.3884	0.4855	0.5141	0.5371
CT	0.3584	0.3792	0.4643	0.4944	0.5345
MT	0.3282	0.3818	0.4396	0.4705	0.5140

Results of FTIR Tests From Previous Research

SPEC	ORIGINAL	NO AGING	6 MONTH	1 YEAR	2 YEAR	3 YEAR
AM	0.3406	0.4264	0.5041	0.5232	0.5498	0.5973
BE	0.3054	0.4215	0.4947	0.5154	0.5925	0.6253
BO	0.3821	0.4428	0.5388	0.5536	0.5871	0.6038
CH	0.4212	0.4471	0.4886	0.5266	0.6114	0.6345
ES	0.3441	0.4396	0.5127	0.5435	0.6300	0.6644
MA	0.3008	0.4148	0.4933	0.5175	0.6329	0.6312
TA	0.7618	0.8643	0.8837	0.8876	1.0200	1.0085
TX	0.2693	0.4304	0.4767	0.5321	0.6262	0.6182

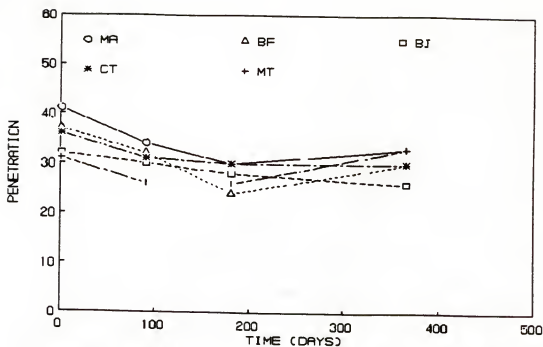


Figure 7.13 Penetration vs. Time (Natural Weathering Samples)

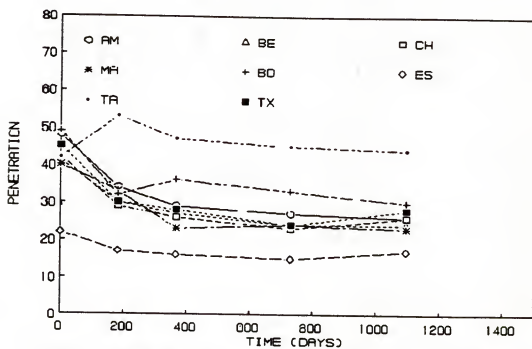


Figure 7.14 Penetration vs. Time (Natural Weathering Samples from Previous Research)

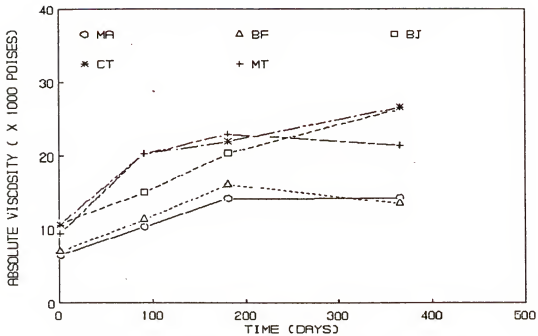


Figure 7.15 Absolute Viscosity at 140 °F vs. Time
(Natural Weathering Samples)

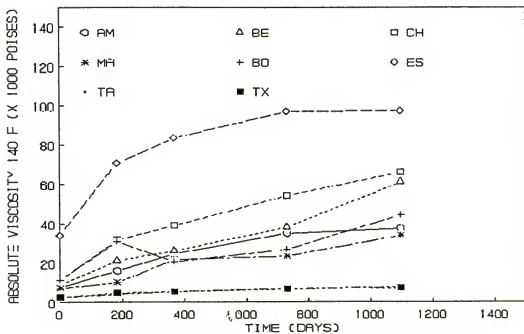


Figure 7.16 Absolute Viscosity at 140 °F vs. Time
(Natural Weathering Samples from Previous Research)

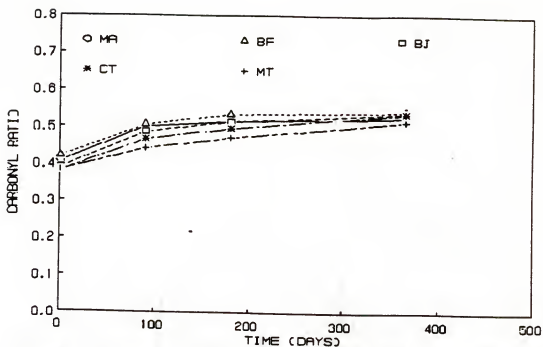


Figure 7.17 Carbonyl Ratio vs. Time (Natural Weathering Samples)

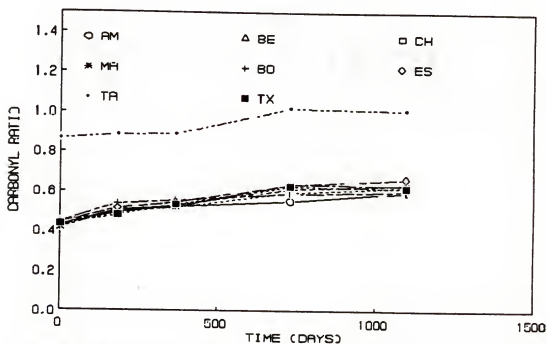


Figure 7.18 Carbonyl Ratio vs. Time (Natural Weathering Samples from Previous Research)

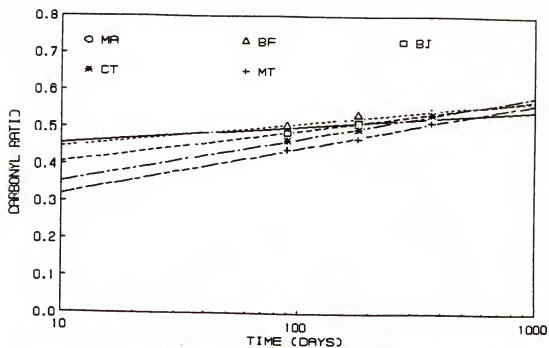


Figure 7.19 Carbonyl Ratio vs. Time (Natural Weathering Samples)

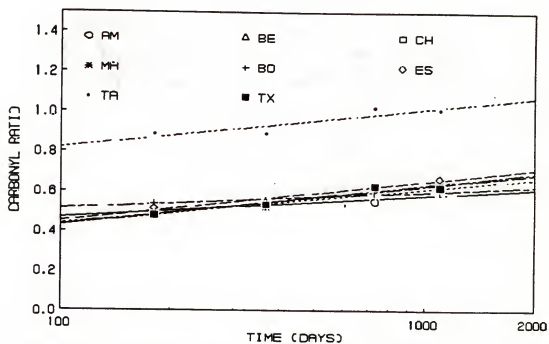


Figure 7.20 Carbonyl Ratio vs. Time (Natural Weathering Samples from Previous Research)

Table 7.4 Constant Power Viscosity Results

			NO AGING	3 MONTH	6 MONTH	1 YEAR
MA	15°C	C	0.7235	0.6706	0.6827	0.5803
	15°C	Nj	3.201E7	4.00E7	4.747E7	4.772E7
	25°C	C	0.9075	0.8642	0.7948	0.9810
	25°C	Nj	7.806E5	1.427E6	3.145E6	1.268E6
BF	15°C	C	0.6620	0.6760	0.6632	0.6652
	15°C	Nj	5.368E7	4.597E8	7.131E7	5.480E7
	25°C	C	0.9650	0.8797	0.9917	0.7406
	25°C	Nj	5.078E5	2.227E6	2.817E6	3.885E6
BJ	15°C	C	0.6730	0.5799	0.4709	0.6009
	15°C	Nj	5.629E7	5.973E7	1.132E8	7.722E7
	25°C	C	0.7950	0.8773	0.6259	0.9672
	25°C	Nj	3.549E6	1.687E6	8.153E6	2.235E6
CT	15°C	C	0.6140	0.5181	0.5114	0.5325
	15°C	Nj	4.631E7	6.766E7	8.494E7	8.835E7
	25°C	C	0.7925	0.7305	0.6641	0.8718
	25°C	Nj	1.654E6	2.702E6	3.896E6	2.151E6
MT	15°C	C	0.8485	0.6076	0.5864	0.5230
	15°C	Nj	2.128E7	4.842E7	9.101E7	9.263E7
	25°C	C	0.8915	0.7064	0.6263	0.9559
	25°C	Nj	1.418E6	7.295E6	8.294E6	2.796E6

Table 7.5 Constant Power Viscosity Test Results

			NO AGING	1 YEAR	2 YEAR	3 YEAR
AM	15°C	C	0.8445	0.6023	0.5829	0.6469
	15°C	Nj	5.679E6	6.798E7	7.745E7	8.244E7
	25°C	C	0.9073	0.7852	0.6544	0.6230
	25°C	Nj	4.143E5	3.901E6	7.403E6	8.145E6
BE	15°C	C	0.7406	0.5045	0.3903	0.4100
	15°C	Nj	1.322E7	7.653E7	1.909E8	1.880E8
	25°C	C	0.8178	0.7037	0.6871	0.6973
	25°C	Nj	1.020E6	3.637E6	5.806E6	8.696E6
BO	15°C	C	0.8446	0.6734	0.5925	0.5916
	15°C	Nj	8.131E6	3.952E7	4.541E7	8.688E7
	25°C	C	0.7433	0.6872	0.6604	0.6304
	25°C	Nj	8.3364E5	2.4039E6	4.013E6	6.738E6
CH	15°C	C	0.7949	0.5203	0.5319	0.4890
	15°C	Nj	1.516E7	6.170E7	7.497E7	9.913E7
	25°C	C	0.7320	0.6111	0.6503	0.6628
	25°C	Nj	1.467E6	5.802E6	6.533E6	8.449E6
MA	15°C	C	0.9171	0.5111	0.4371	0.4300
	15°C	Nj	8.710E6	1.249E8	1.962E8	2.010E8
	25°C	C	0.9084	0.7362	0.8091	0.7530
	25°C	Nj	7.564E5	4.856E6	6.674E6	7.147E6

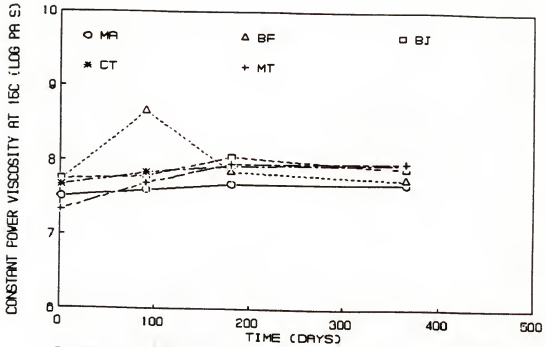


Figure 7.21 Constant Power Viscosity at 15 °C vs. Time
(Natural Weathering Samples)

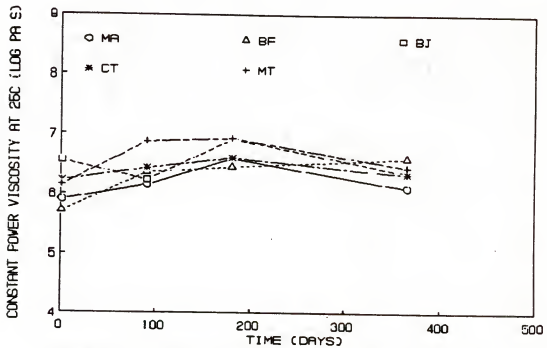


Figure 7.22 Constant Power Viscosity at 25 °C vs. Time
(Natural Weathering Samples)

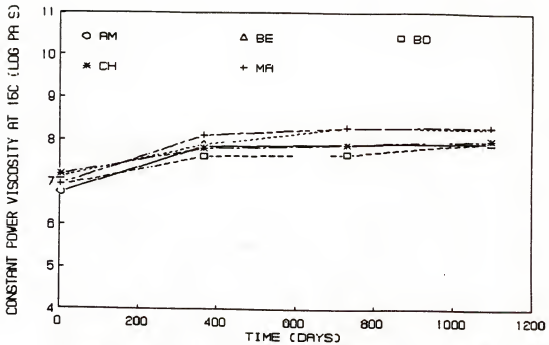


Figure 7.23 Constant Power Viscosity at 15 °C vs. Time (Natural Weathering Samples from Previous Research)

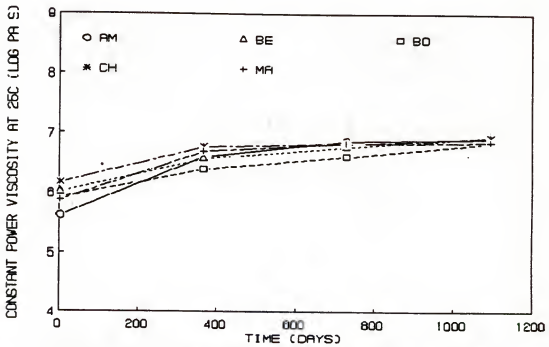


Figure 7.24 Constant Power Viscosity at 25 °C vs. Time (Natural Weathering Samples from Previous Research)

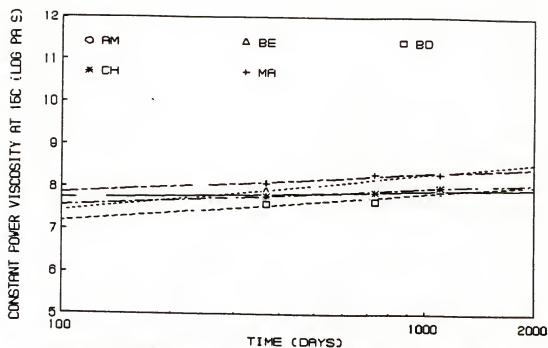


Figure 7.25 Constant Power Viscosity at 15 °C vs. Time
(Natural Weathering Samples from Previous Research)

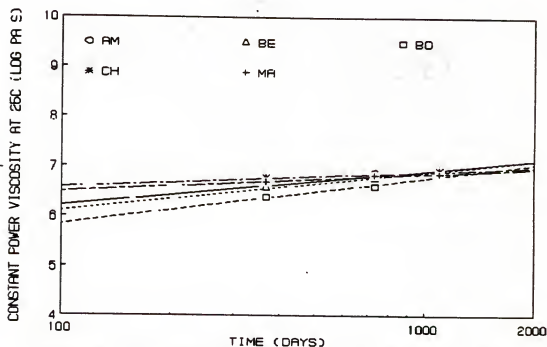


Figure 7.26 Constant Power Viscosity at 25 °C vs. Time
(Natural Weathering Samples from Previous Research)

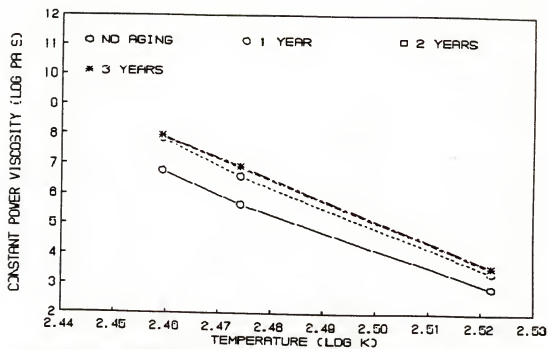


Figure 7.27 Constant Power Viscosity vs. Temperature (Roof AM)

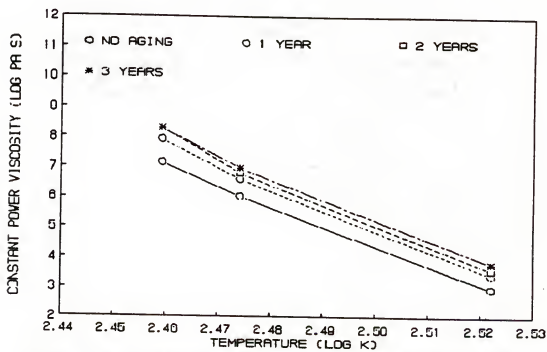


Figure 7.28 Constant Power Viscosity vs. Temperature (Roof BE)

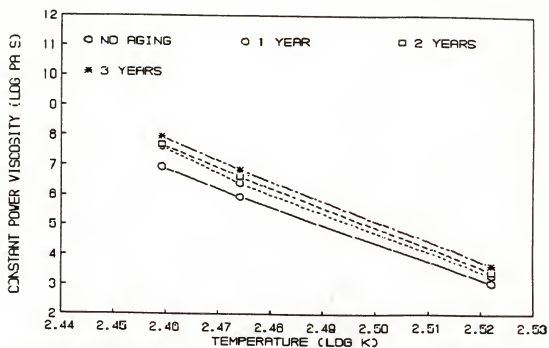


Figure 7.29 Constant Power Viscosity vs. Temperature (Roof B0)

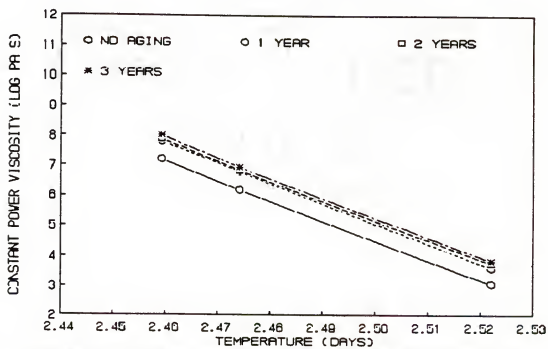


Figure 7.30 Constant Power Viscosity vs. Temperature (Roof CH)

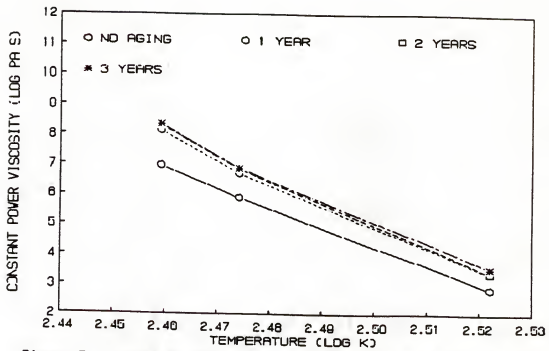


Figure 7.31 Constant Power Viscosity vs. Temperature (Roof MA)

7.2 Core Samples From Asphalt Concrete Pavements

The three selected sections of asphalt concrete pavements are I-75, US-301 section 1, and US-301 section 2 in Hernando County, Florida. Core samples were taken from the pavements periodically. Tests described in the beginning of this chapter were performed on the core samples and the recovered asphalts. Tables 7.6 and 7.7 show the results of the indirect tensile test on the core samples. Results of the fracture energy are shown in Tables 7.8 and 7.9. Results of the penetration, absolute viscosity at 140 °F, and FTIR on the recovered asphalts are shown in Table 7.10. Table 7.11 shows the results of the Schwyer rheometer test on the recovered asphalts.

Figures 7.32 through 7.34 show the indirect tensile strength vs. time of the core samples. From Figure 7.34, the indirect tensile strength vs. time for core samples from US 301 section 2, it is seen that the WP samples have little higher strength than BWP samples. It probably because the WP is more densified by the traffic. Figures 7.35 through 7.37 show the fracture energy of the core samples. The fracture energy results do not show any consistent trend.

The relationship of penetration, absolute viscosity, and carbonyl ratio vs. time are presented in Figures 7.38 through 7.40, respectively. The penetration value decreases as the asphalt ages. While the absolute viscosity and the carbonyl ratio increase with time. Table 7.11 shows the constant power viscosity of core samples. Figure 7.41 shows the viscosity-temperature relationship of the asphalt used in I-75. It is seen that the viscosity-temperature relationship shifts parallel to the original relationship as the asphalt ages. It can be seen that the shoulder asphalt ages much more severe than do the WP and BWP samples.

Table 7.6 Results of Indirect Tensile Test on I75

DURATION		TEMP.		SPEC	HT	LOAD	STRESS
YEARS	('F)	TYPE	#	(inch)	(lbs)	(psi)	
2	41	WP	1	1.855	4000.0	336.33	
2	41	WP	2	1.666	2950.0	276.18	
			AVG	1.761	3475.0	306.25	
2	41	BWP	1	1.467	3250.0	345.54	
2	41	BWP	2	1.522	3025.0	310.00	
			AVG	1.495	3137.5	327.77	
3	41	WP	23	1.595	3025.0	295.81	
3	41	WP	24	1.606	3025.0	293.78	
			AVG	1.601	3025.0	294.80	
3	41	BWP	19	1.453	3300.0	354.24	
3	41	BWP	20	1.435	2525.0	274.45	
			AVG	1.444	2912.5	314.34	
4	41	WP	1	1.928	4625.0	374.15	
4	41	WP	2	1.719	3875.0	351.59	
			AVG	1.824	4250.0	362.87	
4	41	BWP	5	1.560	2850.0	284.95	
4	41	BWP	6	1.694	3425.0	315.35	
			AVG	1.627	3137.5	300.15	
2	77	WP	3	1.767	1825.0	161.09	
2	77	WP	4	1.652	1900.0	179.39	
			AVG	1.710	1862.5	170.24	
2	77	BWP	3	1.463	1500.0	159.92	
2	77	BWP	4	1.454	1750.0	187.72	
			AVG	1.459	1625.0	173.82	
3	77	WP	25	1.598	1700.0	165.93	
3	77	WP	26	1.578	1962.5	193.98	
			AVG	1.588	1831.3	179.95	
3	77	BWP	21	1.566	1812.5	180.52	
3	77	BWP	22	1.529	1712.5	174.69	
			AVG	1.548	1762.5	177.61	
4	77	WP	3	1.783	2087.5	182.61	
4	77	WP	4	1.891	2187.5	180.43	
			AVG	1.837	2137.5	181.52	
4	77	BWP	7	1.709	1787.5	163.14	
4	77	BWP	8	1.625	1687.5	161.97	
			AVG	1.667	1737.5	162.55	

Table 7.7 Results of Indirect Tensile test on US301

DURATION YEARS	TEMP. (°F)	SECTION	TYPE	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)
2	41	SEC#1	WP	13	0.867	1762.5	317.07
2	41	SEC#2	WP	19	0.981	2412.5	383.57
2	41	SEC#1	BWP	16	0.760	1025.0	210.36
2	41	SEC#2	BWP	22	0.831	1962.5	368.35
3	41	SEC#1	WP	17	1.841	5150.0	436.31
3	41	SEC#1	WP	18	1.876	5112.5	425.06
				AVG	1.859	5131.3	430.69
3	41	SEC#1	BWP	13	1.458	2775.0	296.86
3	41	SEC#1	BWP	14	1.480	2487.5	262.15
				AVG	1.469	2631.3	279.50
3	41	SEC#2	WP	21	1.345	3462.5	401.53
3	41	SEC#2	WP	22	1.485	3562.5	374.17
				AVG	1.415	3512.5	387.85
3	41	SEC#2	BWP	25	1.137	2700.0	370.38
3	41	SEC#2	BWP	26	1.147	2762.5	375.65
				AVG	1.142	2731.3	373.02
2	77	SEC#1	WP	11	0.781	962.5	192.22
2	77	SEC#1	WP	12	0.891	1037.5	181.62
				AVG	0.836	1000.0	186.92
2	77	SEC#1	BWP	14	0.794	725.0	142.42
2	77	SEC#1	BWP	15	0.936	787.5	131.23
				AVG	0.865	756.3	136.82
2	77	SEC#2	WP	17	1.046	1356.3	202.23
2	77	SEC#2	WP	18	0.841	1037.5	192.41
				AVG	0.944	1196.9	197.32
2	77	SEC#2	BWP	20	0.861	968.8	175.49
2	77	SEC#2	BWP	21	0.919	1050.0	178.21
				AVG	0.890	1009.4	176.85
3	77	SEC#1	WP	19	1.851	2287.5	192.75
3	77	SEC#1	WP	20	1.865	2375.0	198.62
				AVG	1.858	2331.3	195.69
3	77	SEC#1	BWP	15	1.477	1318.8	139.26
3	77	SEC#1	BWP	16	1.408	1206.3	133.62
				AVG	1.443	1262.5	136.44
3	77	SEC#2	WP	23	1.513	2025.0	208.75
3	77	SEC#2	WP	24	1.604	2206.3	214.53
				AVG	1.559	2115.6	211.64
3	77	SEC#2	BWP	27	1.212	1437.5	184.99
3	77	SEC#2	BWP	28	1.247	1537.5	192.31
				AVG	1.230	1487.5	188.65

Table 7.8 Fracture Energy on I-75

DURATION YEAR	TEMP. (F)	POSITION	SPEC#	ENERGY (Pascal)
2 YR	41	WP	1	2516.01
2 YR	41	WP	2	1441.62
2 YR	41	BWP	1	838.41
2 YR	41	BWP	2	1673.56
3 YR	41	WP	23	2342.65
3 YR	41	WP	24	1331.23
3 YR	41	BWP	19	3202.80
3 YR	41	BWP	20	1173.84
4 YR	41	WP	1	1757.72
4 YR	41	WP	2	1155.39
4 YR	41	BWP	5	3375.49
4 YR	41	BWP	6	0.00
2 YR	77	WP	3	2175.09
2 YR	77	WP	4	2510.64
2 YR	77	BWP	3	2037.27
2 YR	77	BWP	4	2547.03
3 YR	77	WP	25	1470.80
3 YR	77	WP	26	2350.53
3 YR	77	BWP	21	581.55
3 YR	77	BWP	22	1230.18
4 YR	77	WP	3	3394.96
4 YR	77	WP	4	3240.94
4 YR	77	BWP	7	3319.44
4 YR	77	BWP	8	3328.40

Table 7.9 Fracture Energy on US-301

DURATION YEAR	TEMP. (F)	POSITION	SECTION	SPEC#	ENERGY (Pascal)
2 YR	41	WP	#1	13	0.00
2 YR	41	WP	#2	19	2330.70
2 YR	41	BWP	#1	16	426.28
2 YR	41	BWP	#2	22	2092.35
3 YR	41	WP	#1	17	3549.21
3 YR	41	WP	#1	18	3831.27
3 YR	41	BWP	#1	13	2145.27
3 YR	41	BWP	#1	14	1545.79
3 YR	41	WP	#2	21	1907.50
3 YR	41	WP	#2	22	2402.88
3 YR	41	BWP	#2	25	2109.97
3 YR	41	BWP	#2	26	2602.08
2 YR	77	WP	#1	11	1550.81
2 YR	77	WP	#1	12	1651.23
2 YR	77	BWP	#1	14	1181.60
2 YR	77	BWP	#1	15	1038.47
2 YR	77	WP	#2	17	2306.46
2 YR	77	WP	#2	18	1993.38
2 YR	77	BWP	#2	20	1546.25
2 YR	77	BWP	#2	21	2488.95
3 YR	77	WP	#1	19	2496.23
3 YR	77	WP	#1	20	2720.11
3 YR	77	BWP	#1	15	1581.96
3 YR	77	BWP	#1	16	1642.25
3 YR	77	WP	#2	23	2860.65
3 YR	77	WP	#2	24	3203.68
3 YR	77	BWP	#2	27	2578.67
3 YR	77	BWP	#2	28	3031.12

Table 7.10 Penetration, Absolute Viscosity, and Carbonyl Ratio Test Results

SITE	TIME	SECT#	POSITION	PEN	VIS(140°F)	CR
US301	ORI			73	2246	0.3254
US301	PAVER	1		53	5932	-
US301	PAVER	2		38	7980	-
US301	3MON	1	WP	36	15958	-
US301	3MON	1	BWP	35	14019	-
US301	3MON	2	WP	35	17234	-
US301	3MON	2	BWP	38	10165	0.5274
US301	1YEAR	2	WP	39	10732	0.5102
US301	1YEAR	2	BWP	36	13780	0.5750
US301	2YEAR	1	WP	30	30266	0.6187
US301	2YEAR	1	BWP	30	25932	0.5557
US301	2YEAR	2	WP	30	22127	0.5501
US301	2YEAR	2	BWP	34	18464	0.5437
US301	3YEAR	1	WP	27	50510	0.5896
US301	3YEAR	1	BWP	27	46350	0.5831
US301	3YEAR	2	WP	26	38316	0.5754
US301	3YEAR	2	BWP	30	19907	0.5675
I75	ORI			75	2111	0.3595
I75	PAVER			47	10416	-
I75	10DAY		WP	42	11508	0.5596
I75	10DAY		BWP	42	10030	0.4646
I75	3MON		WP	37	12650	0.5220
I75	3MON		BWP	37	13509	0.6144
I75	6MON		WP	41	8727	0.4950
I75	6MON		BWP	34	14061	0.5463
I75	1YEAR		WP	39	8935	0.5014
I75	1YEAR		BWP	36	12800	0.5526
I75	2YEAR		WP	32	19737	0.5378
I75	2YEAR		BWP	28	29669	0.5748
I75	3YEAR		WP	30	20658	0.5450
I75	3YEAR		BWP	29	27436	0.5754
I75	4YEAR		WP	39	10159	-
I75	4YEAR		BWP	36	12912	-

Table 7.11 Constant Power Viscosity of Core Samples From Field

			Constant Power Viscosity (Pa S)	
			15°C	25°C
I75	1YEAR	WP	-	8.60E05
I75	1YEAR	BWP	-	1.40E06
I75	2YEAR	WP	1.03E08	5.41E06
I75	2YEAR	BWP	8.43E07	1.06E07
I75	3YEAR	WP	3.68E07	2.06E07
I75	3YEAR	BWP	1.67E07	1.02E07
US301	6MON	WP	-	2.12E06
SECT	6MON	BWP	-	1.80E06
#1	2YEAR	WP	2.61E07	7.80E06
	2YEAR	BWP	1.86E07	3.54E06
	3YEAR	WP	1.19E08	5.49E06
	3YEAR	BWP	1.58E07	5.29E06
US301	6MON	WP	-	1.57E06
SECT	6MON	BWP	-	1.32E06
#2	2YEAR	WP	4.39E07	4.21E06
	2YEAR	BWP	4.73E07	3.37E06
	3YEAR	WP	1.21E08	4.40E06
	3YEAR	BWP	2.01E08	5.32E06

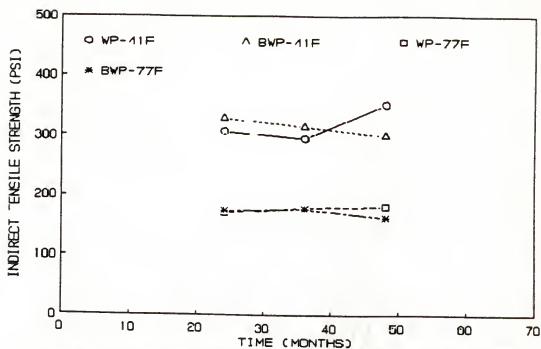


Figure 7.32 Indirect Tensile Strength vs. Time (I-75 Cores)

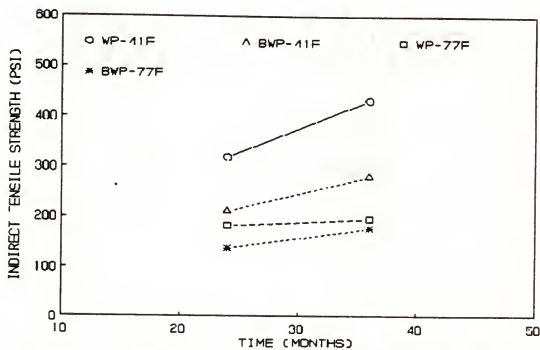


Figure 7.33 Indirect Tensile Strength vs. Time (US-301 Sect. 1)

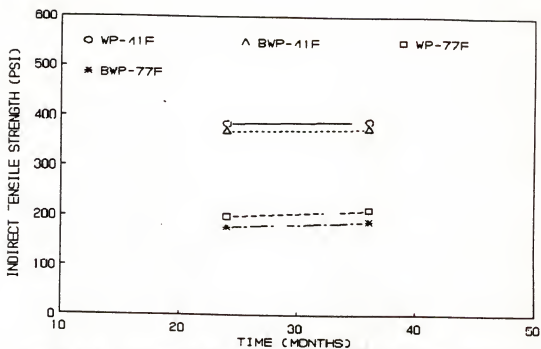


Figure 7.34 Indirect Tensile Strength vs. Time (US-301 Sect. 2)

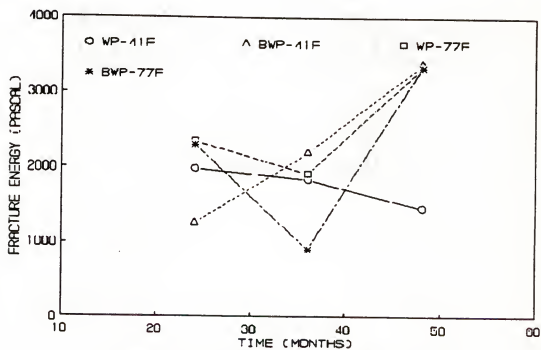


Figure 7.35 Fracture Energy vs. Time (I-75)

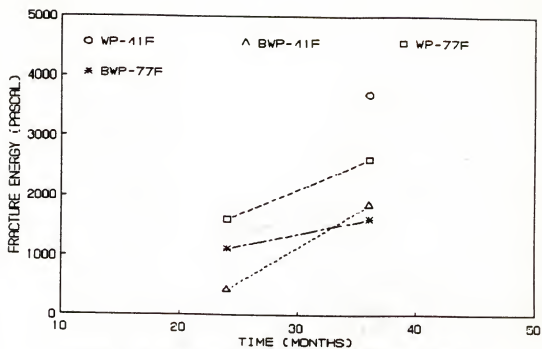


Figure 7.36 Fracture Energy vs. Time (US-301 sect. 1)

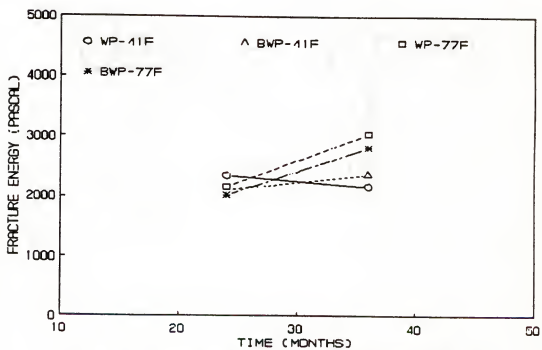


Figure 7.37 Fracture Energy vs. Time (US-301 Sect. 2)

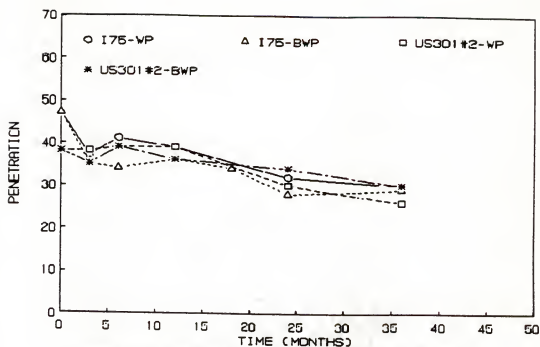


Figure 7.38 Penetration vs. Time (Cores from Roads)

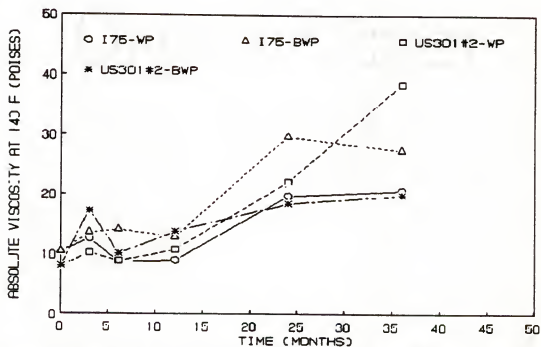


Figure 7.39 Absolute Viscosity at 140 °F vs. Time (Samples from Roads)

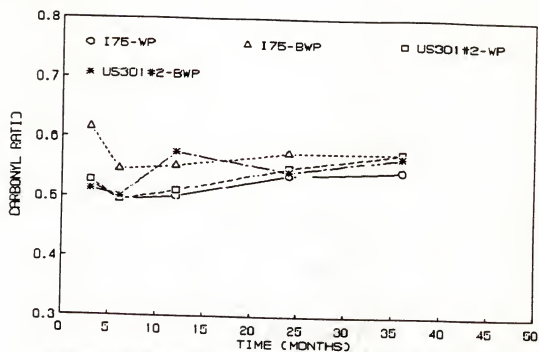


Figure 7.40 Carbonyl Ratio vs. Time (Samples from Roads)

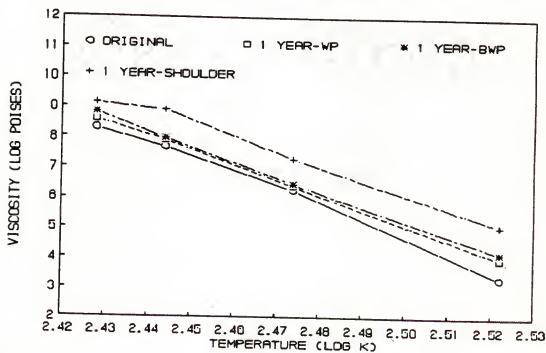


Figure 7.41 Viscosity vs. Temperature (I-75)

CHAPTER 8 ANALYSIS AND DISCUSSION

8.1 TFOT and RTFOT Procedures

The TFOT and the RTFOT tests were adopted by AASHTO, ASTM, and almost all state highway departments and other governmental agencies as specification tests [60]. The AASHTO and ASTM standards states: "This method indicates approximate change in properties of asphalt during conventional hot-mixing at about 302 °F (150 °C) as indicated by viscosity, penetration or ductility measurements. It yields a residue which approximates the asphalt condition as incorporated in the pavement. If the mixing temperature differs appreciably from the 302 °F level, more or less effect on properties will occur."

Results of the tests on asphalt binders presented in Chapter 6, has demonstrated that higher oven temperatures result in increased differentials in properties. For example, the change in viscosity ratio between 325 °F and 365 °F is greater than that between 285 °F and 325 °F. The higher test temperature of 365 °F would magnify the asphalt properties change as compared to the lower test temperature of 325 °F. The TFOT and RTFOT were compared and discussed in Chapter 6. It is found that on the basis of percent penetration retained and absolute viscosity ratio, the RTFOT effect is slightly more severe than TFOT for oven temperatures of 285 and 325 °F. But at 365 °F, there is no significant difference between the TFOT and RTFOT. On the basis of Carbonyl ratio, the effects of TFOT and RTFOT are not significantly

different from each other for oven temperatures of 285 and 325 °F. But at 365 °F, the TFOT is a more severe aging process than the RTFOT. From the stand point of constant power viscosity, the effects of TFOT and RTFOT are not significantly different from each other at all three levels of temperature. Therefore, there is no particular reason to favor the RTFOT process over the TFOT process, especially if the test temperature is raised to 365°F.

Comparison was done between the residues after TFOT and RTFOT at 365 °F, recovered asphalts from the specimens aged on the roof under natural weathering, and recovered asphalts from the core samples on the roads. Tables 8.1 through 8.3 show the comparisons. It appears that the TFOT and RTFOT procedures performed at 365 °F, fourteen days aging at 140 °F in the laboratory, and three months of natural weathering, would result in approximately the same hardening effects on a typical paving grade asphalt used in Florida. The hardening effects of twenty-eight days aging at 140 °F in the laboratory are equivalent to those of the six months natural weathering. The hardening effects of ninety days aging at 140 °F in the laboratory are more severe than those of three years natural weathering.

From Table 8.3, the twenty-eight days aging in the laboratory and twelve to eighteen months aging in the road would result in approximately identical hardening effects. Natural weathering of Marshall specimens for six months also results in hardening effects which are approximately equivalent to twenty-eight days aging in the laboratory. Therefore, Marshall specimens that are allowed to weather naturally for six months would harden approximately two to three times as much as the mixtures when placed and compacted in a pavement. Since

Table 8.1 Comparison of Aging Effect

		TFOT (365°F)	RTFOT (365°F)	ROOF(MON.)		LAB(DAYS)	
				3	6	14	28
PEN.	MA	34	33	34	30	33	32
	BF	28	28	32	24	30	26
	BJ	32	28	30	28	28	27
	CT	-	32	31	30	33	31
	MT	31	29	26	26	29	27
VIS.	MA	10583	11492	10313	14171	9987	11426
	BF	12267	12267	11310	16074	11150	15515
	BJ	15501	24079	14959	20353	16136	20900
	CT	10599	12285	20239	21931	16555	21399
	MT	16429	17832	20225	22904	14251	19556
CR.	MA	.4045	.3870	.4979	.5140	.4551	.5014
	BF	.4735	.4601	.5027	.5333	.4861	.5182
	BJ	.3674	.3761	.3761	.4855	.5141	.4914
	CT	.4622	.4288	.4643	.4944	.4371	.5010
	MT	.3869	.3577	.4396	.4705	.4414	.4880
CPV. (77°F)	MA	4.39E6	3.22E6	1.43E6	3.15E6	1.83E6	3.93E6
	BF	6.17E6	6.52E6	2.23E6	2.82E6	2.40E6	3.35E6
	BJ	4.88E6	4.74E6	1.69E6	8.15E6	4.12E6	7.18E6
	CT	4.09E6	4.28E6	2.70E6	3.90E6	2.91E6	4.25E6
	MT	2.73E6	2.68E6	7.30E6	8.29E6	2.31E6	4.73E6
CPV (59°F)	MA	5.24E7	7.04E7	4.00E7	4.75E7	6.64E7	6.71E7
	BF	1.07E8	1.25E8	4.60E8	7.13E7	8.11E7	1.42E8
	BJ	1.52E8	2.16E8	5.97E7	1.13E8	1.14E8	1.00E8
	CT	1.26E8	9.35E7	6.77E7	8.49E7	6.59E7	6.69E7
	MT	1.24E8	6.51E7	4.84E7	9.10E7	8.09E7	9.56E7

Table 8.2 Comparison Between Natural Weathering and Lab. Aging

		NATURAL WEATHERING		LAB. AGING
		2 YEARS	3 YEARS	(90 DAYS)
PEN.	AM	27	26	21
AT	BE	24	24	23
77°F	BO	33	30	21
	CH	23	26	21
	ES	15	17	15
	MA	24	23	22
	TA	45	44	42
	TX	24	28	21
VIS.	AM	34930	37424	150984
AT	BE	38121	60959	61605
140°F	BO	26792	44427	81106
POISE	CH	54162	65981	103262
	ES	96941	97325	893298
	MA	23429	34059	40504
	TA	7010	7910	8559
	TX	6673	7335	10173
CR.	AM	.5498	.5973	.6336
	BE	.5925	.6253	.6452
	BO	.5871	.6038	.6753
	CH	.6114	.6345	.6650
	ES	.6300	.6644	.6980
	MA	.6329	.6312	.6889
	TA	1.020	1.0085	.9635
	TX	.6262	.6182	.6568

Table 8.3 Comparison Between Field Aging and Lab. Aging

	Field Aging						Lab Aging	
	1Y	I-75 2Y	3Y	1Y	US-301 2Y	3Y	28 (DAYS)	90
ABS. VIS. AT 140°F (POISES)	13400	24703	24047	10806	20296	29112	15523	33584
PEN. AT 77°F	35	30	29	.39	32	28	35	25
CARBONYL RATIO	.5500	.5563	.5602	.5300	.5469	.5715	.5592	.6606

the hardening effects of ninety days aging at 140 °F in the laboratory are more severe than that of three years natural weathering, the hardening effects of ninety days aging at 140 °F in the laboratory should be more severe than those of six to nine years aging on the roads. This is understandable considering the larger area of surface exposed to weather in a Marshall specimen as compared to that of a core of similar dimensions from the pavement.

New tests have recently been developed to simulate the changes of asphalt properties during service. Kemp and Predoehl [49] developed the California tilt-oven asphalt durability test which was based primarily on the Rolling Thin Film procedure with the difference that the temperature was lowered to 235.4 °F (113 °C) and the weathering period extended to 168 hours (7 days). Lowering the temperature caused the asphalt to build up in the bottles and this problem was addressed by tilting the oven so that the front was slightly higher. The California tilt-oven asphalt durability test was recommended to be used to predict asphalt hardening caused by two years of aging in the typical desert weather of California.

Another laboratory oxidative aging procedures [60] for asphalt cements and asphalt mixtures involved using a pressure oxygen vessel (POV), a sealed container in which asphalt mixtures or asphalt samples were subjected to pure oxygen at 100 psi pressure at 60 °C for periods of up to 5 days. It was claimed that asphalts aged in the POV for 5 days had composition similar to that of those recovered from field cores that were from 5 to 10 years old.

8.2 Relationships Between Mixture Properties and Asphalt Viscosity

The response and failure of asphalt concrete pavements have been shown to be highly dependent on the properties of the asphalt cement. Attempts were made to find the relationships between mixture properties and constant power viscosity. Figure 8.1 shows the relationship of indirect tensile strength vs. constant power viscosity. The air void of the specimens tested in this project is approximately five percent. The relationship can be defined by the equation

$$S_t = -136.88 + 10.32 \log_{10}(\text{CPV}) + 6.00 [\log_{10}(\text{CPV})]^2 \quad (8.1)$$

where

S_t = Indirect tensile strength, psi

CPV = Constant power viscosity, pa.s, $\leq 1 \text{ E9 pa.s}$

$R^2 = 0.9535$.

When the constant power viscosity is higher than 1 E9 pa.s, the indirect tensile strength levels off or even drops off. It is found from the equation that the highest indirect strength is 442 psi when the constant power viscosity of the asphalt is 1 E9 pa.s. Ruth et. al. [64] found the maximum indirect tensile strength was 400 psi. Variations in materials and compacted density can result in variation of ± 25 percent or more in the maximum stress.

Figure 8.2 shows the total resilient modulus and instantaneous resilient modulus vs. constant power viscosity. The linear relationship for the instantaneous and the total resilient moduli can be defined as follow

$$\log_{10}(\text{RMI}) = 5.254 + 0.0288 \log_{10}(\text{CPV}) \quad (8.2)$$

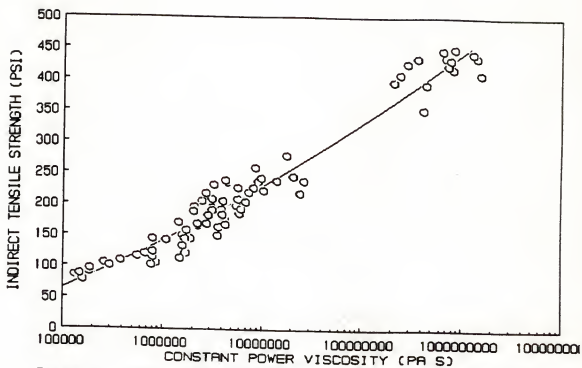


Figure 8.1 Indirect Tensile Strength vs. Constant Power Viscosity

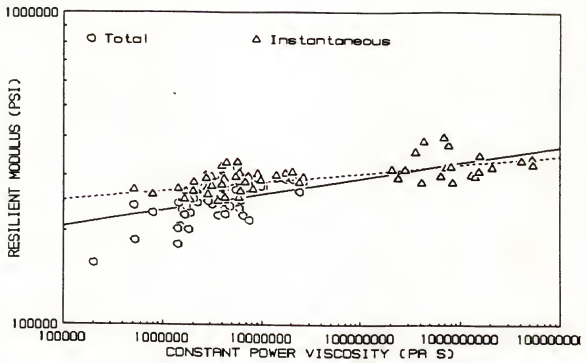


Figure 8.2 Resilient Modulus vs. Constant Power Viscosity

$$\log_{10}(\text{RMT}) = 5.061 + 0.0509 \log_{10}(\text{CPV}) \quad (8.3)$$

where

RMI = instantaneous resilient modulus, psi

RMT = total resilient modulus, psi

CPV = constant power viscosity, pa.s

$R^2 = 0.4986$ for the instantaneous resilient modulus,

0.6046 for the total resilient modulus.

From Figure 8.2, the resilient moduli increase as the constant power viscosity is higher. But when the constant power viscosity is higher than 1 E9 pa.s , the resilient moduli level off. When the asphalt is soft, the instantaneous resilient modulus is higher than the total resilient modulus. However, when the asphalt is hard, the difference between the instantaneous and the total resilient moduli becomes smaller. When the constant power viscosity is greater than 5 E8 pa.s , there is no difference between the instantaneous and the total resilient moduli. It is understandable since when asphalts become harder, the creep component would diminish.

Figure 8.3 shows the fracture energy vs. constant power viscosity. The scattering of the data may be attributable to the method of measurement used in the test. The strains calculated from LVDT's reading are not necessarily the true strains in the middle of the specimen. However, from Figure 8.3, the trend still can be seen. The fracture energy increases when the constant power viscosity increases until the constant power viscosity reaches around 1 E8 pa.s . Then the fracture energy drops when the constant power viscosity is greater than 1 E8 to 1 E9 pa.s .

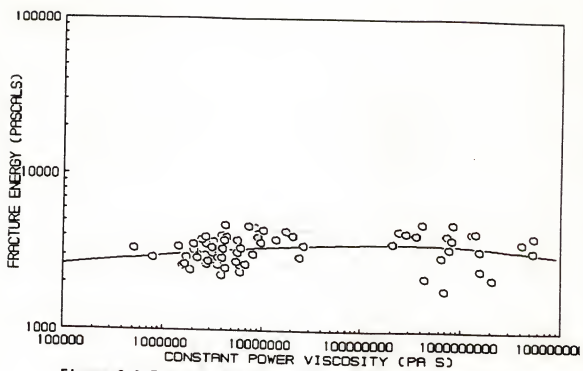


Figure 8.3 Fracture Energy vs. Constant Power Viscosity

8.3 IR Spectral Evaluation of Asphalt Hardening

Oxidation is the primary cause of the asphalt hardening. Several chemical functional groups are formed in the asphalt due to the oxidation process. It is found that the FTIR is a very simple and effective method to identify the chemical functional groups formed during oxidation of the asphalt. From the results presented in the earlier chapters, the carbonyl ratio can be used to follow the level of oxidation of asphalts.

The relationship between the carbonyl ratio and the constant power viscosity at 77 °F is illustrated in Figure 8.4. It is found that the carbonyl ratio increases as the constant power viscosity increases. The relationship can be defined by the equation

$$CR = -0.5271 + 0.1554 \log_{10}(CPV) \quad (8.4)$$

where

CR = carbonyl ratio

CPV = constant power viscosity at 77 °F, pa.s

$R^2 = 0.7099$.

8.4 Comparison of Laboratory Exposure Types

The three laboratory exposure types, i.e. convectional oven, ultraviolet chamber, and forced draft oven, were evaluated by comparing the strength of the asphalt mixtures, and the viscosities, penetration, and IR spectral absorbance of the asphalt binder at a level of significance of 0.05. The results presented in Chapter 7 indicated that the asphalts hardened most severely in the convection oven, and least

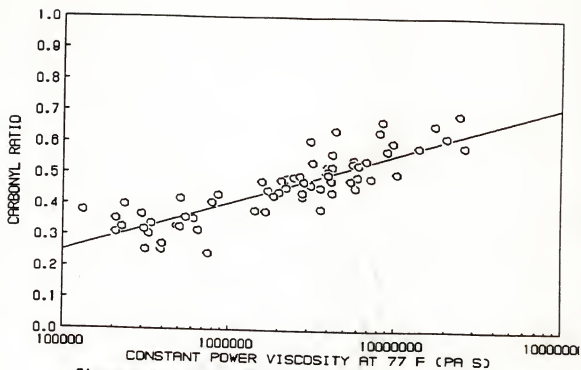


Figure 8.4 Carbonyl Ratio vs. Constant Power Viscosity

severely in the ultraviolet chamber. It is believed that the oxidation is the primary factor in asphalt hardening. The convectional oven used in this research project was a big oven. There was plenty of air in the oven and additional fresh air could flow in whenever the door was opened for checking temperature or arranging specimens. The convectional oven acted as an effective draft oven in this study. That could explain why the asphalts aged more severely in the convectional oven.

The effects of ultraviolet exposure might be predominantly on the outer periphery of the specimens. The interiors would be relatively less influenced and so the effects would be diminished when the asphalt is recovered from the whole specimen. This appears to be one of the reasons why asphalts did not harden more in the ultraviolet chamber.

From the discussion above, it appears that the most effective way to simulate aging process could well be a combination of heat and oxygen. The forced draft oven could be a good tool to simulate the aging process.

8.5 Hardening Trend of Asphalt

Ruth et al. [47] reported that there was a fairly linear relationship between log of the test parameter and log age in days in the previous analyses of Florida age hardening data. The results presented in the earlier chapters show that the absolute viscosity at 60 °C and the constant power viscosity at 25 °C fit the relationship described above. It is found that the indirect tensile strength at 77 °F, penetration at 77 °F, and carbonyl ratio all have linear relationships against log time in days, with the exclusion of the no aging data.

There is linear relationship between log constant power viscosity and log temperature in °K as illustrated in earlier chapters. It is found that the asphalt constant power viscosity - temperature relationship is shifted parallel to the original relationship after an asphalt ages. The linear relationship shifts farther as the asphalt ages longer.

8.6 Pavement Stress Analyses

Empirical relationships between pavement response and pavement performance are very important for evaluation and design of pavement systems. Generally, two relationships have been used, one for prediction of cracking of bound layers (e.g., asphalt concrete) and one for prediction of permanent deformations (roughness or rutting) of the base course and subgrade layers. Maximum tensile stress or strain at the bottom of AC layer, and the vertical stress or strain on top of the subgrade are used as criteria. These are used to compute the remaining life of the pavement and overlay required to meet established criteria. The horizontal tensile stress at the bottom of the bound layer is assumed critical in evaluating the pavement's resistance to cracking.

The traffic-load-induced fatigue is usually considered the cause of cracking of asphalt-bound layers in the existing pavement design procedures. However, Ruth et. al. [64,65] reported that cracking was a short-term phenomenon that occurred when the combined effect of temperature and traffic loads exceed the failure limit of the asphalt concrete pavement. The permanent deformations of the base course and subgrade layers are beyond of the scope of this study. However, this

section demonstrates how the properties of asphalt can affect the performance of pavements.

In a research study done in the University of Florida [66], the BISAR elastic layer computer program was used to calculate pavement response induced by vehicular loadings at low temperature conditions. A 24-kip single axle with dual tires at 120 psi (13.0 in. between wheel centers) was used to represent truck loading conditions. Asphalt concrete moduli for the various pavement sections were computed using the rheology relationship at two low temperatures. These were 23 °F and 41 °F to represent winter conditions in northern, and southern Florida, respectively.

Table 8.4 shows the summary of the stress analyses. A maximum failure tensile stress of 400 psi was considered a typical value for fracture stress of dense graded asphalt concrete mixtures when subjected to a short-term loading at low temperatures [64]. Prior investigations [64] indicate that pavements can crack when stress levels are in the range of 64 percent to 70 percent of the failure stress. Therefore, when the combined effect of load and thermal-induced stresses are considered, three out of the five pavements would be susceptible to cracking. This conclusion was confirmed by field observations.

It was concluded that a pavement's resistance to load-induced cracking could be improved by using a lower viscosity asphalt to eliminate excessively high asphalt concrete moduli at the minimum pavement temperatures. Therefore, the properties of asphalts at low temperature are very important factors to pavement performance.

In another research study [67], a computer program REDAPS was developed to evaluate pavement systems. The REDAPS (REhabilitation

Table 8.4 Summary of Pavement Stress Analysis at Low Temperature [66]

Test Road	SR 268	SR24	US441	SR15C	SR-80- #1 #2	
Temp. (*F)	23	23	23	41	41	41
NDT Device	Dynaflect	Dynaflect	Dynaflect	Dynaflect	Dynaflect	
Max. Deflection (mils)	13.0	8.1	10.0	15.9	32.0	38.5
Subgrade Compression (%)	83.0	44.9	58.2	82.4	43.4	24.7
Subgrade Strain* (0.0001 in./in.)	1.66	0.88	1.55	1.61	1.91	2.06
AC Stress** (psi)	89.0	182.0	208.0	54.4	207	344
% of AC Failure Stress+	22.3	45.5	52.0	13.6	51.8	86.0

* Vertical compressive strain on top of subgrade layer

** Tensile stress at bottom of AC layer

+ Failure tensile stress of 400 psi

Design of Asphalt Pavement Systems) was based on the critical condition concept rather than the conventional fatigue failure criterion. The computer program utilized a multilayered linear elastic pavement model and incorporated material properties, distress criteria, combined effects of temperature, asphalt binder aging hardening and vehicular loading in pavement evaluations and rehabilitation designs.

Effect of age hardening rate of asphalts was investigated in a case study in the research. Five different asphalt age hardening rates were used in the study. Same cooling condition and vehicular load were used in all cases. It was found that the theoretical life of the pavement was reduced from more than 40 years to only 3 years when the binder hardening rate (the slope of log viscosity vs. log time) was increased from 0.65 to 0.90. It was summarized that the life of an asphalt concrete pavement was governed by the asphalt binder age hardening rate, the environmental temperature condition, foundation support, the magnitude and volume of traffic. Under a given climatic and traffic conditions, the life of an asphalt concrete pavement with a sound base can be extended through the use of softer and less aging susceptible asphalts.

It is demonstrated that the use of softer asphalts would reduce the problem of cracking in asphalt concrete pavements during the colder weather. However, when choosing asphalts for pavement construction, the increased potential for rutting, which might be associated with the use of softer asphalts, must be considered as well.

8.7 Low Temperature Cracking Limit

According to the research conducted by Ruth et al. [68] for the Florida Department of Transportation over the past 10 years, when the maximum stress ratio is less than 0.30, the pavement is considered to be in good structural condition. If the stress ratio exceeds 0.55, immediate rehabilitation may be necessary. Therefore, under the minimum regional temperature, a pavement with stress ratio over 0.30 is likely to have cracking problem.

Given a typical pavement section, by limiting the stress ratio under 0.30, the maximum dynamic modulus of asphalt concrete under the minimum regional temperature can be found. The BISAR elastic layer computer program was used to calculate pavement response by vehicular loading at low temperature condition. A 24-kip single axle load with dual tires at 120 psi (13 in. between wheel centers) was used to represent truck loading conditions. A typical pavement section was chosen and is shown in Table 8.5.

The maximum indirect tensile strength of 400 psi is selected [64]. The maximum stress allowed at the bottom of the asphalt concrete layer is therefore 120 psi. It is found that the maximum dynamic modulus of asphalt concrete is $1.315 \text{ E}6 \text{ psi}$ when the stress at the bottom of the asphalt concrete layer is 121 psi. From the relationship established by Ruth et al. [64],

when $9.19 \text{ E}8 \leq (\text{CPV}) \leq 2.07 \text{ E}10 \text{ pa.s}$,

$$\log(E1) = 9.51354 + 0.04716 \log(\text{CPV}) \quad (8.5)$$

where

$E1$ = dynamic modulus of asphalt concrete, Pa

Table 8.5 Typical Pavement Section and Input Parameters for BISAR

Layer Description		Thickness (inch)	Poisson's Ratio	Modulus (psi)
1	Asphalt Concrete	6	0.35	1315000
2	Limerock Base	12	0.35	90000
3	Subbase	18	0.35	40000
4	Subgrade	semi- infinite	0.45	8000

CPV = constant power viscosity, Pa.s,
 the constant power viscosity under the condition is found to be $2.59 \text{ E}9 \text{ Pa.s}$. Therefore, $2.59 \text{ E}9 \text{ Pa.s}$ is the low temperature cracking limit. Under the typical pavement section, if the constant power viscosity of asphalt is higher the $2.59 \text{ E}9 \text{ Pa.s}$ at the minimum regional temperature, the asphalt concrete is likely to have low temperature cracking problem. Davis [69] reported that the primary specification for the control of asphalt should be a maximum viscosity of $2.1 \text{ E}9 \text{ Pa.s}$ at the expected lowest temperature. Exceeding this viscosity could lead to thermal cracking. This value is reasonably close to the value derived earlier in this section.

8.8 Improved Specifications for Asphalt Durability

Improvements to specifications can be made in order to permit selection of materials to achieve performance levels required by the present and projected traffic loading and environmental exposure of the pavement. Current specifications of asphalt are not enough to ensure having good long term performance of the pavement. TFOT and RTFOT procedures simulate only short term aging process. It is necessary to have an aging process to simulate the long term aging on the roads. From the results of this study and the discussion earlier in this chapter, it is possible to utilize TFOT or RTFOT at higher temperature for longer period of time, or forced draft oven to simulate the long term aging process on the roads. By limiting the property changes (or hardening rate) after the aging process, low durability asphalt can be eliminated.

The low temperature cracking limit can be used to eliminate the low temperature cracking problem. Under the regional minimum temperature, the constant power viscosity of the aged asphalt, which simulate 5 or 10 years of aging on the road, must be lower than 2.56 E9 pa.s. The regional maximum temperature must be considered too, since the asphalt concrete must be stiff enough to support the traffic loading during summer time. Therefore, low temperature susceptibility is desirable when choosing asphalts for pavement constructions.

CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

A research study was conducted on the age hardening trends of typical asphalt binders in laboratory controlled aging environments and in actual paving projects. The following conclusions were derived from the results obtained in this investigation:

1. On the basis of percent penetration retained and absolute viscosity ratio, the RTFOT is a more severe aging process than the TFOT for oven temperatures of 285 and 325 °F. However, the two processes are not significantly different from each other at an oven temperature of 365 °F.
2. On the basis of carbonyl ratio, the effects of TFOT and RTFOT are not significantly different from each other at oven temperatures of 285 and 325 °F. But at 365 °F, the TFOT is a more severe aging process than the RTFOT from the stand point of carbonyl ratio.
3. On the basis of constant power viscosity at 41 and 77 °F, the effects of TFOT and RTFOT are not significantly different from each other at all three levels of temperature.
4. As a rough estimate, it is probable that the TFOT or RTFOT procedure performed at 365 °F, fourteen days aging at 140 °F in the laboratory, and three months of natural weathering

would result in approximately the same hardening effects on a typical paving grade asphalt used in Florida.

5. As a rough estimate, it is probable that the hardening effects of ninety days aging in the laboratory oven at 140 °F are more severe than that of six to nine years aging on the roads.
6. A relationship between the indirect tensile strength of Marshall specimen for the mixtures studied and the constant power viscosity of asphalt was established. The equation is shown in Section 9.2. It is found that the ultimate indirect tensile strength of Marshall specimens is 442 psi when the constant power viscosity of asphalt is near or greater than 1 E9 pa.s .
7. Relationships of the total resilient modulus and instantaneous resilient modulus for the mixtures studied vs. the constant power viscosity were established. The equations are shown in Section 9.2. When the asphalt is soft, the instantaneous resilient modulus is higher than the total resilient modulus. However, when the asphalt is hard, the difference between the instantaneous and the total resilient moduli becomes smaller. When the constant power viscosity of asphalt is greater than 5 E8 pa.s , there is no difference between the instantaneous and total resilient moduli.
8. As the asphalts harden, the fracture energy increases to a maximum and then decreases. The maximum fracture energy is reached when the constant power viscosity of asphalt is around 1 E8 pa.s .

9. Infrared spectroscopic techniques can be used to sensitively assess changes in the asphalt due to increased levels of oxidation. The carbonyl ratio, which is a ratio of absorbance at 1700 cm^{-1} and 1600 cm^{-1} , increases with increasing levels of oxidative hardening of the asphalt.
10. A relationship between the carbonyl ratio and the constant power viscosity of asphalt was determined for the asphalts studied and presented in section 9.4. The carbonyl ratio increases as the constant power viscosity increases.
11. The constant power viscosity - temperature relationship of asphalt is shifted parallel to the original relationship as the asphalt ages. The relationship shifts farther when the asphalt ages longer.
12. The combination of fresh air and heat can be utilized effectively to accelerate the aging process of asphalt binders and mixtures.
13. The hardening trend of asphalt, generally, shows a fairly linear relationship between the test parameter and log age in days, or between log of the test parameter and log age in days.
14. The low temperature cracking limit is found to be 2.6 E9 pa.s . In a typical pavement, if the constant power viscosity of asphalt is higher than 2.6 E9 pa.s at the minimum regional temperature, the asphalt concrete is likely to have low temperature cracking problem.

9.2 Recommendations

The following recommendations for further study, based on the results obtained in this investigation, are suggested:

1. The thin film oven test and rolling thin film oven test should be considered to be performed at higher temperature and for longer period of time to simulate aging for a period of time in field.
2. An investigation should be performed on the hardening behavior of asphalts by using the California tilt oven test and the pressure oxygen bomb as the aging processes.
3. The forced draft oven is a good device to accelerate the aging process. Further study is needed on the hardening effects of loose asphalt mixtures by using the forced draft oven. It is believed that since the air void of the loose asphalt mixture is much larger, the age hardening effect would be much more severe than that on the Marshall specimen. Therefore, it would require shorter time to simulate the aging process on the roads.
4. Further investigation on age hardening of asphalts by using infrared spectroscopy is needed. A large database would be necessary to establish the relationship between the carbonyl ratio and the hardening characteristics of the asphalts.
5. More pavement performance data are needed to establish the relationship between aging in the field and aging in the laboratory. Subsequently, criteria can be established to ensure satisfactory long-term performance.

APPENDIX A

PROPERTIES OF MARSHALL SPECIMENS

Table A.1 Density and Air Void of Marshall Specimens

MA30						
	Wt. in air (g)	Wt. in water (g)	SSD (g)	SG	Unit Wt. (pcf)	% Air Void
MA 1	1110.60	606.60	1113.10	2.193	136.82	4.46
MA 2	1113.80	608.10	1115.90	2.193	136.87	4.43
MA 3	1122.10	610.90	1126.10	2.178	135.91	5.10
MA 4	1119.70	612.20	1121.60	2.198	137.16	4.22
MA 5	1115.20	608.90	1117.00	2.195	136.96	4.36
MA 6	1115.80	607.40	1119.40	2.179	135.99	5.04
MA 7	1120.50	610.30	1124.00	2.181	136.11	4.96
MA 8	1117.10	606.90	1120.00	2.177	135.85	5.13
MA 9	1116.30	609.50	1119.90	2.187	136.48	4.70
MA10	1122.30	609.60	1125.70	2.175	135.69	5.25
MA11	1117.40	609.40	1119.20	2.192	136.77	4.49
MA12	1120.30	607.60	1122.70	2.175	135.71	5.23
MA13	1119.20	608.30	1121.40	2.181	136.11	4.96
MA14	1117.60	607.80	1119.10	2.186	136.39	4.76
MA15	1121.60	610.10	1123.80	2.183	136.24	4.86
MA16	1121.60	610.00	1124.10	2.182	136.14	4.94
MA17	1121.40	608.60	1123.30	2.179	135.95	5.07
MA18	1109.30	601.60	1111.20	2.177	135.83	5.15
MA19	1121.80	610.60	1123.30	2.188	136.53	4.66
MA20	1104.30	599.70	1106.10	2.181	136.07	4.98
MA21	1110.10	603.20	1112.10	2.181	136.12	4.95
MA22	1117.60	609.20	1119.60	2.190	136.63	4.59
MA23	1117.00	608.60	1119.00	2.188	136.56	4.64
MA24	1119.40	611.50	1121.50	2.195	136.96	4.36
MA25	1123.60	611.40	1126.60	2.181	136.09	4.97
MA26	1119.80	608.10	1122.60	2.176	135.81	5.16
MA27	1115.70	607.70	1117.40	2.189	136.59	4.62
MA28	1121.80	609.80	1124.10	2.181	136.11	4.96
MA29	1119.00	608.80	1121.60	2.182	136.17	4.92
MA30	1117.70	606.80	1121.10	2.173	135.61	5.31
MA31	1114.60	604.80	1118.00	2.172	135.52	5.37
MA32	1110.80	604.20	1113.70	2.180	136.04	5.00
MA33	1106.30	602.70	1108.00	2.189	136.62	4.60
MA34	1107.90	604.00	1109.40	2.192	136.79	4.48
MA35	1120.00	611.40	1121.20	2.197	137.09	4.27
MA36	1116.10	608.90	1117.50	2.194	136.93	4.38
MA37	1117.50	606.70	1118.80	2.182	136.17	4.92
MA38	1118.50	605.80	1120.10	2.175	135.71	5.24
MA39	1120.40	609.00	1122.60	2.181	136.12	4.95
MA40	1120.70	609.70	1122.30	2.186	136.43	4.74

Table A.1 -- continued

MA41	1121.90	610.00	1123.10	2.187	136.44	4.73
MA42	1118.40	608.70	1120.20	2.187	136.44	4.73
MA43	1117.30	607.60	1119.50	2.183	136.20	4.90
MA44	1119.00	609.20	1120.70	2.188	136.51	4.68
MA45	1120.40	611.00	1121.40	2.195	136.98	4.35
MA46	1119.60	610.40	1121.40	2.191	136.72	4.53
MA47	1118.50	609.40	1120.00	2.191	136.69	4.55
MA48	1120.00	611.30	1121.90	2.193	136.87	4.42
MA49	1124.40	610.60	1127.10	2.177	135.84	5.14
MA50	1116.20	609.40	1118.40	2.193	136.84	4.45
MA51	1119.30	610.30	1120.90	2.192	136.79	4.48
MA52	1118.70	607.30	1120.70	2.179	135.97	5.05
MA53	1122.10	609.60	1123.80	2.182	136.17	4.91
MA54	1117.80	608.70	1119.30	2.189	136.61	4.61
MA55	1121.40	610.20	1122.90	2.187	136.48	4.70
MA56	1122.20	610.30	1124.40	2.183	136.21	4.89
MA57	1120.00	609.10	1122.20	2.183	136.21	4.89
MA58	1120.60	609.80	1122.80	2.184	136.31	4.82
MA59	1118.20	609.30	1120.10	2.189	136.60	4.61
MA60	1118.30	609.00	1120.50	2.186	136.43	4.74
AVG				2.185	136.35	4.79
VAR				0.0000	0.1652	0.0805
STD				0.0065	0.4064	0.2838

Table A.1 -- continued

BF30

	Wt. in air (g)	Wt. in water (g)	SSD (g)	SG	Unit Wt. (pcf)	% Air Void
BF 1	1109.60	601.60	1112.80	2.171	135.44	5.59
BF 2	1117.90	607.00	1120.90	2.175	135.74	5.38
BF 3	1123.80	610.20	1125.90	2.179	135.98	5.21
BF 4	1119.70	609.30	1121.90	2.184	136.30	4.99
BF 5	1121.60	607.30	1123.30	2.174	135.64	5.45
BF 6	1125.10	613.10	1127.70	2.186	136.43	4.90
BF 7	1119.10	608.00	1121.50	2.179	135.99	5.20
BF 8	1121.20	608.60	1123.40	2.178	135.90	5.27
BF 9	1119.60	613.50	1121.40	2.204	137.55	4.12
BF10	1119.30	608.10	1121.10	2.182	136.15	5.09
BF11	1125.20	611.20	1126.90	2.182	136.15	5.09
BF12	1120.40	609.80	1122.40	2.186	136.39	4.93
BF13	1118.30	605.20	1120.80	2.169	135.34	5.66
BF14	1120.80	607.80	1122.20	2.179	135.96	5.23
BF15	1123.20	606.40	1125.70	2.163	134.97	5.92
BF16	1123.90	608.40	1125.40	2.174	135.65	5.44
BF17	1118.90	606.90	1121.10	2.176	135.78	5.35
BF18	1124.50	608.30	1126.90	2.168	135.30	5.68
BF19	1124.80	612.70	1126.10	2.191	136.71	4.70
BF20	1117.30	609.00	1119.00	2.191	136.70	4.71
BF21	1118.10	612.80	1119.60	2.206	137.67	4.04
BF22	1123.90	611.70	1125.80	2.186	136.42	4.91
BF23	1123.50	608.20	1125.30	2.173	135.58	5.49
BF24	1122.10	611.30	1125.40	2.183	136.20	5.06
BF25	1126.40	614.20	1128.30	2.191	136.72	4.70
BF26	1126.40	609.00	1128.80	2.167	135.22	5.74
BF27	1118.60	608.80	1120.60	2.186	136.38	4.93
BF28	1116.70	610.40	1117.90	2.200	137.30	4.29
BF29	1113.80	603.90	1115.70	2.176	135.80	5.34
BF30	1120.70	606.60	1122.50	2.172	135.55	5.51
BF31	1125.70	606.50	1127.30	2.161	134.88	5.98
BF32	1124.90	607.70	1127.20	2.165	135.12	5.81
BF33	1116.20	605.70	1117.40	2.181	136.12	5.12
BF34	1118.60	604.30	1119.90	2.170	135.38	5.63
BF35	1119.30	607.60	1121.00	2.180	136.04	5.17
BF36	1116.60	605.60	1118.10	2.179	135.95	5.23
BF37	1123.00	605.90	1126.30	2.158	134.66	6.14
BF38	1122.00	605.30	1124.00	2.163	134.98	5.91
BF39	1121.00	603.60	1123.30	2.157	134.60	6.18
BF40	1120.20	606.10	1121.50	2.173	135.62	5.46

Table A.1 -- continued

BF41	1116.50	601.70	1118.70	2.160	134.76	6.06
BF42	1122.60	606.10	1125.20	2.163	134.95	5.93
BF43	1120.00	607.90	1123.20	2.173	135.63	5.46
BF44	1116.10	605.10	1119.10	2.171	135.50	5.55
BF45	1122.00	604.60	1124.80	2.157	134.59	6.18
BF46	1120.10	607.40	1122.70	2.174	135.64	5.45
BF47	1118.60	603.60	1120.80	2.163	134.96	5.92
BF48	1120.40	610.40	1122.80	2.187	136.44	4.89
BF49	1123.80	608.60	1126.30	2.171	135.46	5.58
BF50	1120.00	606.80	1121.10	2.178	135.89	5.28
BF51	1123.30	606.60	1124.00	2.171	135.47	5.57
BF52	1119.40	603.50	1121.60	2.161	134.82	6.02
BF53	1120.70	603.60	1123.50	2.156	134.51	6.24
BF54	1123.50	605.90	1125.60	2.162	134.90	5.97
BF55	1120.90	604.40	1123.20	2.161	134.82	6.02
BF56	1118.60	604.00	1120.40	2.166	135.17	5.78
BF57	1118.70	602.90	1121.60	2.157	134.58	6.19
BF58	1127.00	607.70	1129.40	2.160	134.80	6.04
BF59	1122.90	609.00	1125.90	2.172	135.56	5.51
BF60	1119.90	604.00	1123.20	2.157	134.60	6.18
AVG				2.174	135.65	5.44
VAR				0.0001	0.5463	0.2654
STD				0.0118	0.7391	0.5152

Table A.1 -- continued

MT30

	Wt. in air (g)	Wt. in water (g)	SSD (g)	SG	Unit Wt. (pcf)	% Air Void
MT 1	1115.20	605.10	1117.10	2.178	135.92	4.76
MT 2	1112.20	605.00	1114.10	2.185	136.32	4.48
MT 3	1122.00	608.60	1124.80	2.174	135.63	4.96
MT 4	1126.80	618.00	1129.20	2.204	137.54	3.62
MT 5	1122.50	610.80	1124.70	2.184	136.30	4.49
MT 6	1119.70	607.70	1121.80	2.178	135.91	4.77
MT 7	1124.40	612.50	1126.50	2.188	136.50	4.35
MT 8	1116.90	603.70	1119.40	2.166	135.15	5.30
MT 9	1118.10	606.00	1120.50	2.173	135.61	4.98
MT10	1122.60	611.60	1124.60	2.188	136.55	4.32
MT11	1121.90	608.70	1123.40	2.180	136.01	4.69
MT12	1117.90	606.90	1119.80	2.180	136.00	4.70
MT13	1121.30	610.70	1123.00	2.189	136.58	4.30
MT14	1118.50	605.60	1120.40	2.173	135.58	5.00
MT15	1119.60	607.50	1122.60	2.174	135.63	4.96
MT16	1123.00	608.90	1125.40	2.174	135.67	4.93
MT17	1121.10	608.40	1122.50	2.181	136.08	4.65
MT18	1122.10	608.00	1123.70	2.176	135.77	4.86
MT19	1120.00	612.00	1122.00	2.196	137.04	3.98
MT20	1123.80	611.80	1125.20	2.189	136.59	4.29
MT21	1126.10	609.30	1127.60	2.173	135.58	5.00
MT22	1117.60	605.30	1119.40	2.174	135.65	4.95
MT23	1124.20	611.50	1126.30	2.184	136.27	4.51
MT24	1117.30	606.60	1120.60	2.174	135.64	4.95
MT25	1123.60	609.80	1125.90	2.177	135.85	4.81
MT26	1119.20	605.20	1122.50	2.164	135.00	5.40
MT27	1122.80	609.60	1125.90	2.175	135.70	4.91
MT28	1121.50	613.00	1124.50	2.193	136.82	4.13
MT29	1118.50	607.60	1120.80	2.179	136.00	4.70
MT30	1117.80	605.60	1120.50	2.171	135.46	5.08
MT31	1115.60	604.20	1117.60	2.173	135.59	4.99
MT32	1114.40	603.80	1116.20	2.175	135.71	4.90
MT33	1120.90	606.20	1123.20	2.168	135.29	5.20
MT34	1118.10	605.90	1120.30	2.174	135.63	4.96
MT35	1115.60	603.40	1117.20	2.171	135.49	5.06
MT36	1126.60	609.20	1128.30	2.170	135.43	5.10
MT37	1116.40	602.70	1118.80	2.163	134.98	5.42
MT38	1120.10	605.20	1122.40	2.166	135.14	5.30
MT39	1121.60	606.90	1123.20	2.172	135.56	5.01
MT40	1117.10	603.50	1119.20	2.166	135.17	5.28

Table A.1 -- continued

MT41	1116.70	602.10	1119.10	2.160	134.78	5.55
MT42	1117.50	602.80	1120.00	2.161	134.83	5.52
MT43	1124.50	606.80	1126.40	2.164	135.04	5.37
MT44	1118.80	604.60	1120.60	2.168	135.30	5.19
MT45	1123.40	605.30	1125.50	2.160	134.76	5.57
MT46	1119.00	603.30	1120.70	2.163	134.95	5.43
MT47	1122.70	609.50	1125.10	2.177	135.87	4.79
MT48	1122.30	607.10	1123.90	2.172	135.51	5.04
MT49	1125.10	608.60	1126.40	2.173	135.59	4.99
MT50	1119.80	604.60	1120.80	2.169	135.37	5.15
MT51	1119.50	603.50	1121.30	2.162	134.91	5.46
MT52	1116.80	602.00	1120.00	2.156	134.53	5.73
MT53	1123.00	606.80	1126.60	2.160	134.81	5.53
MT54	1122.20	606.00	1124.10	2.166	135.16	5.29
MT55	1121.40	605.10	1124.40	2.159	134.75	5.58
MT56	1119.60	605.20	1121.90	2.167	135.21	5.25
MT57	1121.00	608.50	1124.10	2.174	135.67	4.93
MT58	1122.00	605.20	1124.40	2.161	134.85	5.51
MT59	1117.20	601.70	1118.80	2.161	134.82	5.53
MT60	1125.00	608.10	1126.20	2.171	135.50	5.05
AVG				2.173	135.61	4.98
VAR				0.0001	0.3734	0.1834
STD				0.0098	0.6111	0.4282

Table A.1 -- continued

BJ30A

	Wt. in air (g)	Wt. in water (g)	SSD (g)	SG	Unit Wt. (pcf)	% Air Void
BJ 1	1106.50	599.00	1108.10	2.173	135.62	5.99
BJ 2	1119.30	607.50	1121.00	2.180	136.02	5.72
BJ 3	1121.90	614.60	1123.20	2.206	137.65	4.59
BJ 4	1121.30	613.80	1122.00	2.206	137.68	4.57
BJ 5	1120.70	616.00	1122.10	2.214	138.18	4.22
BJ 6	1120.70	612.20	1123.20	2.193	136.85	5.14
BJ 7	1121.50	609.20	1122.60	2.184	136.31	5.52
BJ 8	1120.20	613.90	1121.90	2.205	137.60	4.62
BJ 9	1129.10	620.10	1130.60	2.212	138.01	4.34
BJ10	1124.60	615.60	1126.00	2.203	137.49	4.70
BJ11	1129.50	618.70	1130.80	2.206	137.63	4.60
BJ12	1121.00	613.90	1122.40	2.205	137.56	4.65
BJ13	1120.10	615.40	1121.20	2.215	138.19	4.22
BJ14	1121.70	612.70	1123.00	2.198	137.16	4.93
BJ15	1130.10	619.10	1131.10	2.207	137.73	4.53
BJ16	1120.40	611.30	1121.90	2.194	136.92	5.09
BJ17	1124.20	612.70	1125.90	2.191	136.69	5.25
BJ18	1126.50	617.20	1128.00	2.205	137.61	4.61
BJ19	1125.40	616.70	1126.10	2.209	137.86	4.44
BJ20	1119.80	610.30	1121.20	2.192	136.77	5.20
BJ21	1117.50	612.30	1118.80	2.206	137.67	4.57
BJ22	1123.20	617.60	1125.20	2.213	138.08	4.29
BJ23	1125.00	615.10	1126.80	2.199	137.19	4.91
BJ24	1122.20	617.10	1123.50	2.216	138.28	4.15
BJ25	1124.60	613.10	1126.90	2.189	136.58	5.33
BJ26	1122.80	612.70	1124.20	2.195	136.98	5.06
BJ27	1122.20	612.90	1123.70	2.197	137.09	4.98
BJ28	1125.70	613.90	1127.80	2.191	136.69	5.26
BJ29	1121.10	614.10	1122.20	2.206	137.68	4.57
BJ30	1123.10	616.10	1124.20	2.210	137.93	4.39
BJ31	1129.70	620.90	1131.30	2.213	138.11	4.27
BJ32	1113.30	609.20	1115.20	2.200	137.29	4.84
BJ33	1117.70	611.00	1118.50	2.202	137.43	4.74
BJ34	1125.30	612.50	1126.50	2.189	136.61	5.31
BJ35	1119.00	608.90	1120.30	2.188	136.54	5.36
BJ36	1128.20	611.00	1129.10	2.178	135.88	5.81
BJ37	1118.80	606.60	1121.30	2.174	135.64	5.98
BJ38	1117.70	604.80	1119.40	2.172	135.53	6.06
BJ39	1120.20	608.90	1121.70	2.184	136.31	5.52
BJ40	1117.30	610.30	1118.30	2.199	137.24	4.87

Table A.1 -- continued

BJ41	1119.80	609.40	1121.20	2.188	136.53	5.36
BJ42	1125.10	614.50	1127.60	2.193	136.83	5.16
BJ43	1121.80	613.00	1122.60	2.201	137.36	4.79
BJ44	1122.30	612.70	1123.30	2.198	137.16	4.93
BJ45	1120.60	611.80	1121.60	2.198	137.16	4.93
BJ46	1124.20	614.60	1126.60	2.196	137.01	5.03
BJ47	1112.70	605.90	1114.20	2.189	136.60	5.32
BJ48	1122.20	610.30	1124.10	2.184	136.29	5.53
BJ49	1130.40	617.70	1131.50	2.200	137.28	4.84
BJ50	1119.80	613.80	1120.30	2.211	137.96	4.37
BJ51	1121.30	613.40	1122.30	2.203	137.49	4.70
BJ52	1120.20	609.90	1121.60	2.189	136.60	5.31
BJ53	1122.00	610.90	1122.90	2.191	136.74	5.22
BJ54	1124.50	616.10	1126.60	2.203	137.45	4.73
BJ55	1122.00	612.00	1123.30	2.194	136.93	5.09
BJ56	1118.40	607.00	1119.40	2.183	136.20	5.59
BJ57	1119.40	608.70	1121.20	2.184	136.29	5.53
BJ58	1123.20	614.60	1124.50	2.203	137.45	4.72
BJ59	1120.20	610.50	1121.80	2.191	136.71	5.24
BJ60	1121.90	611.80	1123.60	2.192	136.78	5.19
AVG				2.197	137.09	4.98
VAR				0.0001	0.4597	0.2209
STD				0.0109	0.6780	0.4700

Table A.1 -- continued

CT30						
	Wt. in air (g)	Wt. in water (g)	SSD (g)	SG	Unit Wt. (pcf)	% Air Void
CT 1	1114.30	607.80	1116.70	2.190	136.63	4.67
CT 2	1114.50	608.60	1116.20	2.196	137.01	4.41
CT 3	1125.40	614.20	1127.50	2.192	136.81	4.55
CT 4	1122.10	610.10	1124.50	2.181	136.12	5.03
CT 5	1118.10	606.30	1120.30	2.175	135.74	5.30
CT 6	1119.30	607.30	1121.60	2.176	135.80	5.25
CT 7	1123.00	609.00	1125.30	2.175	135.73	5.31
CT 8	1121.00	610.10	1123.50	2.183	136.25	4.94
CT 9	1120.80	609.30	1123.50	2.180	136.01	5.11
CT10	1115.00	604.90	1117.00	2.177	135.86	5.21
CT11	1117.70	609.10	1120.30	2.186	136.43	4.81
CT12	1121.50	610.40	1123.40	2.186	136.42	4.83
CT13	1127.40	613.40	1129.90	2.183	136.20	4.97
CT14	1122.70	611.60	1124.70	2.188	136.54	4.74
CT15	1122.50	611.30	1124.30	2.188	136.54	4.74
CT16	1120.20	607.80	1122.80	2.175	135.73	5.30
CT17	1123.70	611.90	1126.00	2.186	136.39	4.84
CT18	1119.60	608.60	1121.60	2.182	136.19	4.99
CT19	1120.20	608.30	1122.30	2.179	135.99	5.12
CT20	1120.60	609.00	1122.70	2.181	136.12	5.03
CT21	1120.10	609.10	1122.20	2.183	136.22	4.96
CT22	1118.70	609.00	1120.70	2.186	136.42	4.82
CT23	1122.40	609.40	1125.10	2.176	135.81	5.25
CT24	1123.00	610.90	1126.20	2.179	135.99	5.12
CT25	1120.40	610.60	1123.30	2.185	136.36	4.86
CT26	1118.80	610.40	1121.30	2.190	136.65	4.66
CT27	1118.00	608.40	1120.40	2.184	136.26	4.94
CT28	1120.90	610.90	1125.00	2.180	136.05	5.08
CT29	1121.00	610.60	1123.90	2.184	136.28	4.92
CT30	1124.60	612.50	1127.90	2.182	136.16	5.01
CT31	1118.90	606.50	1119.80	2.180	136.02	5.10
CT32	1113.40	608.00	1116.10	2.191	136.74	4.60
CT33	1116.00	610.60	1118.20	2.199	137.19	4.28
CT34	1119.80	611.10	1122.50	2.190	136.64	4.67
CT35	1117.40	610.40	1120.30	2.191	136.74	4.60
CT36	1118.00	611.10	1119.80	2.198	137.14	4.32
CT37	1119.50	609.10	1121.90	2.183	136.23	4.96
CT38	1121.40	612.60	1123.90	2.193	136.86	4.52
CT39	1125.40	611.50	1128.20	2.178	135.91	5.18
CT40	1119.10	608.50	1121.70	2.181	136.07	5.07

Table A.1 -- continued

CT41	1122.10	612.00	1124.10	2.191	136.73	4.61
CT42	1121.50	611.60	1123.30	2.192	136.76	4.58
CT43	1119.40	608.10	1121.10	2.182	136.16	5.00
CT44	1120.40	608.40	1122.70	2.178	135.94	5.16
CT45	1121.40	610.50	1123.30	2.187	136.46	4.80
CT46	1122.30	611.50	1124.80	2.186	136.43	4.81
CT47	1123.20	609.70	1125.30	2.178	135.93	5.16
CT48	1120.70	609.40	1122.80	2.183	136.21	4.97
CT49	1122.10	610.60	1123.70	2.187	136.46	4.79
CT50	1120.80	611.00	1123.20	2.188	136.54	4.74
CT51	1119.70	609.40	1122.10	2.184	136.28	4.92
CT52	1119.60	610.20	1122.40	2.186	136.40	4.84
CT53	1120.30	609.90	1122.20	2.187	136.46	4.80
CT54	1122.10	612.50	1125.40	2.188	136.52	4.76
CT55	1123.60	612.20	1127.30	2.181	136.11	5.04
CT56	1117.40	608.00	1119.60	2.184	136.29	4.91
CT57	1123.40	610.30	1125.70	2.180	136.01	5.11
CT58	1122.20	610.50	1124.70	2.182	136.18	4.99
CT59	1118.80	606.70	1121.40	2.174	135.64	5.37
CT60	1121.00	609.20	1123.20	2.181	136.09	5.05
AVG				2.184	136.30	4.91
VAR				0.0000	0.1229	0.0598
STD				0.0056	0.3506	0.2446

Table A.2 Marshall Specimens Treatment Assignment

MA30

	#	OVEN	#	FD OVEN	#	UV	#	NATURAL	
NO AGING	15	136.24							
	21	136.12							
	23	136.56							
	30	135.61							
	AVG	136.13							
14 DAYS	24	136.96	2	136.87	28	136.11	53	136.17	
	11	136.77	18	135.83	3	135.91	44	136.51	
	16	136.14	20	136.07	39	136.12	45	136.98	
	8	135.85	12	135.71	47	136.69	34	136.79	
	AVG	136.43	AVG	136.12	AVG	136.21	AVG	136.61	
28 DAYS	19	136.53	27	136.59	32	136.04	46	136.72	
	29	136.17	4	137.16	35	137.09	52	135.97	
	7	136.11	22	136.63	33	136.62	41	136.44	
	17	135.95	5	136.96	58	136.31	42	136.44	
	AVG	136.19	AVG	136.84	AVG	136.51	AVG	136.39	
90 DAYS	25	136.09	9	136.48	38	135.71	51	136.79	
	6	135.99	10	135.69	31	135.52	43	136.20	
	1	136.82	14	136.39	50	136.84	37	136.17	
	13	136.11	26	135.81	48	136.87	60	136.43	
	AVG	136.25	AVG	136.09	AVG	136.24	AVG	136.40	
							49	135.84	
							56	136.21	
							2 YEARS	59	136.60
								55	136.48
							AVG	136.28	
							54	136.61	
							40	136.43	
							4 YEARS	36	136.93
							57	136.21	
							AVG	136.54	

Note: 3 months, 6 months, and 1 year duration for NATURAL

Table A.2 -- continued

BF30

	#	OVEN	#	FD OVEN	#	UV	#	NATURAL
NO AGING	5	135.64						
	17	135.78						
	18	135.30						
	6	136.43						
	AVG	135.79						
14 DAYS	34	135.38	27	136.38	22	136.42	31	134.88
	26	135.22	8	135.90	41	134.76	25	136.72
	4	136.30	57	134.58	44	135.50	49	135.46
	2	135.74	10	136.15	32	135.12	43	135.63
	AVG	135.66	AVG	135.75	AVG	135.45	AVG	135.67
28 DAYS	3	135.98	13	135.34	33	136.12	60	134.60
	7	135.99	47	134.96	46	135.64	52	134.82
	15	134.97	23	135.58	48	136.44	59	135.56
	29	135.80	20	136.70	55	134.82	9	137.55
	AVG	135.68	AVG	135.65	AVG	135.75	AVG	135.63
90 DAYS	30	135.55	24	136.20	12	136.39	28	137.30
	51	135.47	54	134.90	40	135.62	38	134.98
	11	136.15	16	135.65	39	134.60	45	134.59
	14	135.96	1	135.44	50	135.89	36	135.95
	AVG	135.78	AVG	135.55	AVG	135.62	AVG	135.71
							58	134.80
							19	136.71
					2 YEARS		37	134.92
							35	136.04
							AVG	135.62
							53	134.51
							56	135.17
					4 YEARS		21	137.67
							42	134.95
							AVG	135.57

Note: 3 months, 6 months, and 1 year duration for NATURAL

Table A.2 -- continued

MT30

	#	OVEN	#	FD OVEN	#	UV	#	NATURAL
NO AGING	21	135.58						
	30	135.46						
	10	136.55						
	25	135.85						
	AVG	135.86						
14 DAYS	29	136.00	20	136.59	9	135.61	50	135.37
	18	135.77	8	135.15	5	136.30	46	134.95
	24	135.64	16	135.67	56	135.21	32	135.71
	53	134.81	3	135.63	60	135.50	38	135.14
	AVG	135.56	AVG	135.76	AVG	135.65	AVG	135.29
28 DAYS	1	135.92	27	135.70	57	135.67	40	135.17
	23	136.27	17	136.08	39	135.56	33	135.29
	26	135.00	2	136.32	35	135.49	31	135.59
	14	135.58	45	134.76	42	134.83	13	136.58
	AVG	135.69	AVG	135.71	AVG	135.38	AVG	135.66
90 DAYS	6	135.91	22	135.65	43	135.04	4	137.54
	11	136.01	59	134.82	51	134.91	41	134.78
	52	134.53	15	135.63	47	135.87	37	134.98
	12	136.00	28	136.82	7	136.50	44	135.30
	AVG	135.61	AVG	135.73	AVG	135.58	AVG	135.65
								54 135.16
								19 137.04
								2 YEARS 55 134.75
								36 135.43
								AVG 135.59
								48 135.51
								34 135.63
								4 YEARS 58 134.85
								49 135.59
								AVG 135.39

Note: 3 months, 6 months, and 1 year duration for NATURAL

Table A.2 -- continued

BJ30

	#	OVEN	#	FD OVEN	#	UV	#	NATURAL
NO AGING	18	137.61						
	10	137.49						
	14	137.16						
	28	136.69						
	AVG	137.24						
14 DAYS	24	138.28	27	137.09	29	137.68	21	137.67
	57	136.29	56	136.20	16	136.92	58	137.45
	1	135.62	17	136.69	19	137.86	52	136.60
	30	137.93	9	138.01	36	135.88	35	136.54
	AVG	137.03	AVG	137.00	AVG	137.09	AVG	137.07
28 DAYS	22	138.08	7	136.31	54	137.45	44	137.16
	37	135.64	11	137.63	40	137.24	41	136.53
	13	138.19	23	137.19	45	137.16	51	137.49
	2	136.02	3	137.65	47	136.60	39	136.31
	AVG	136.98	AVG	137.19	AVG	137.11	AVG	136.87
90 DAYS	6	136.85	20	136.77	50	137.96	49	137.28
	8	137.60	26	136.98	31	138.11	48	136.29
	25	136.58	4	137.68	34	136.61	55	136.93
	15	137.73	12	137.56	59	136.71	32	137.29
	AVG	137.19	AVG	137.25	AVG	137.35	AVG	136.95
								33 137.43
								46 137.01
								2 YEARS 60 136.78
								43 137.36
								AVG 137.15
								38 135.53
								5 138.18
								4 YEARS 42 136.83
								53 136.74
								AVG 136.82

Note: 3 months, 6 months, and 1 year duration for NATURAL

Table A.2 -- continued

CT30

	#	OVEN	#	FD OVEN	#	UV	#	NATURAL
NO AGING	17	136.39						
	24	135.99						
	26	136.65						
	7	135.73						
	AVG	136.19						
14 DAYS	28	136.05	12	136.42	20	136.12	43	136.16
	3	136.81	8	136.25	19	135.99	32	136.74
	29	136.28	18	136.19	46	136.43	59	135.64
	11	136.43	30	136.16	53	136.46	45	136.46
	AVG	136.39	AVG	136.25	AVG	136.25	AVG	136.25
28 DAYS	14	136.54	2	137.01	47	135.93	58	136.18
	13	136.20	23	135.81	34	136.64	16	135.73
	6	135.80	25	136.36	40	136.07	49	136.46
	15	136.54	10	135.86	36	137.14	35	136.74
	AVG	136.27	AVG	136.26	AVG	136.45	AVG	136.28
90 DAYS	22	136.42	33	137.19	42	136.76	37	136.23
	21	136.22	4	136.12	55	136.11	41	136.73
	5	135.74	9	136.01	31	136.02	48	136.21
	1	136.63	27	136.26	38	136.86	57	136.01
	AVG	136.25	AVG	136.39	AVG	136.44	AVG	136.29
							51	136.28
							54	136.52
					2 YEARS		56	136.29
							44	135.94
							AVG	136.26
							50	136.54
							60	136.09
					4 YEARS		39	135.91
							52	136.40
							AVG	136.24

Note: 3 months, 6 months, and 1 year duration for NATURAL

APPENDIX B

RESULTS OF MIXTURE STRENGTH TESTS

Table B.1 Results of Indirect Tensile Test

MA30 41°F

DURATION		OVEN			FD OVEN			UV				
DAYS	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)
0 DAY	MA15	2.539	6800.0	417.67								
	MA21	2.509	6375.0	396.35								
	AVG	2.524	6587.5	407.01								
14 DAYS	MA11	2.528	6800.0	419.49	MA02	2.506	7250.0	451.24	MA03	2.540	7025.0	431.32
	MA24	2.521	7225.0	446.94	MA18	2.522	6600.0	408.17	MA28	2.543	7025.0	430.81
	AVG	2.525	7012.5	433.22	AVG	2.514	6925.0	429.70	AVG	2.542	7025.0	431.07
28 DAYS	MA19	2.537	7600.0	467.18	MA04	2.518	7025.0	435.21	MA32	2.543	6875.0	421.73
	MA29	2.548	7025.0	429.97	MA27	2.525	7500.0	463.34	MA35	2.516	6800.0	421.55
	AVG	2.543	7312.5	448.57	AVG	2.521	7262.5	449.27	AVG	2.529	6837.5	421.64
90 DAYS	MA06	2.536	5250.0	322.89	MA09	2.523	7525.0	465.13	MA31	2.552	6275.0	383.51
	MA25	2.557	5300.0	323.29	MA10	2.547	7250.0	443.97	MA38	2.550	6525.0	399.16
	AVG	2.547	5275.0	323.09	AVG	2.535	7387.5	454.55	AVG	2.551	6400.0	391.33

Table B.1 -- continued

MA30 77°F

DURATION		OVEN			FD OVEN			UV				
DAYS	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)
0 DAY	MA23	2.523	2375.0	146.80								
	MA30	2.547	2287.5	140.10								
	AVG	2.535	2331.3	143.45								
14 DAYS	MA08	2.539	2487.5	152.81	MA12	2.556	2725.0	166.31	MA39	2.540	2550.0	156.57
	MA16	2.547	2375.0	145.42	MA20	2.505	2600.0	161.91	MA47	2.526	2562.5	158.23
	AVG	2.543	2431.3	149.11	AVG	2.530	2662.5	164.11	AVG	2.533	2556.3	157.40
28 DAYS	MA07	2.543	3250.0	199.33	MA05	2.518	3125.0	193.60	MA33	2.515	2762.5	171.30
	MA17	2.534	3250.0	200.02	MA22	2.519	3037.5	188.05	MA58	2.535	2912.5	179.17
	AVG	2.539	3250.0	199.68	AVG	2.519	3081.3	190.82	AVG	2.525	2837.5	175.24
90 DAYS	MA01	2.508	3662.5	227.74	MA14	2.527	3562.5	219.89	MA48	2.525	3287.5	203.07
	MA13	2.534	3912.5	240.79	MA26	2.549	3187.5	195.07	MA50	2.529	3350.0	206.61
	AVG	2.521	3787.5	234.26	AVG	2.538	3375.0	207.48	AVG	2.527	3318.8	204.84

Table B.1 -- continued

BF30 41°F

DURATION		OVEN			FD OVEN			UV				
DAYS	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)
0 DAY	BF05	2.538	7050.0	433.26								
	BF17	2.532	6750.0	415.80								
	AVG	2.535	6900.0	424.53								
14 DAYS	BF26	2.558	7100.0	432.92	BF08	2.535	6825.0	419.98	BF22	2.523	7225.0	446.71
	BF34	2.537	7000.0	430.41	BF27	2.557	7000.0	427.04	BF41	2.539	6600.0	405.49
	AVG	2.547	7050.0	431.66	AVG	2.546	6912.5	423.51	AVG	2.531	6912.5	426.10
28 DAYS	BF03	2.535	7000.0	430.69	BF13	2.538	7725.0	474.80	BF33	2.517	6700.0	415.18
	BF07	2.535	7350.0	452.29	BF47	2.526	7225.0	446.18	BF46	2.522	6525.0	403.48
	AVG	2.535	7175.0	441.49	AVG	2.532	7475.0	460.49	AVG	2.520	6612.5	409.33
90 DAYS	BF30	2.547	6550.0	401.05	BF24	2.552	6475.0	395.74	BF12	2.534	7525.0	463.24
	BF51	2.554	6550.0	400.01	BF54	2.571	7250.0	439.88	BF40	2.529	7250.0	447.07
	AVG	2.551	6550.0	400.53	AVG	2.561	6862.5	417.81	AVG	2.532	7387.5	455.15

Table B.1 -- continued

BF30 77°F

DURATION		OVEN			FD OVEN			UV				
DAYS	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)
0 DAY	BF06	2.537	2900.0	178.27								
	BF18	2.553	3087.5	188.63								
	AVG	2.545	2993.8	183.45								
14 DAYS	BF02	2.542	2837.5	174.08	BF10	2.536	3350.0	206.04	BF32	2.552	3125.0	191.02
	BF04	2.531	2875.0	177.17	BF57	2.536	3275.0	201.42	BF44	2.552	3250.0	198.61
	AVG	2.537	2856.3	175.63	AVG	2.536	3312.5	203.73	AVG	2.552	3187.5	194.81
28 DAYS	BF15	2.556	3762.5	229.56	BF20	2.527	3762.5	232.23	BF48	2.543	3625.0	222.34
	BF29	2.537	3987.5	245.15	BF23	2.549	3737.5	228.67	BF55	2.553	3450.0	210.75
	AVG	2.547	3875.0	237.36	AVG	2.538	3750.0	230.45	AVG	2.548	3537.5	216.54
90 DAYS	BF11	2.528	4362.5	269.16	BF01	2.532	4037.5	248.74	BF39	2.549	3875.0	237.08
	BF14	2.528	4662.5	287.70	BF16	2.538	4350.0	267.29	BF50	2.546	3875.0	237.36
	AVG	2.528	4512.5	278.43	AVG	2.535	4193.8	258.02	AVG	2.548	3875.0	237.22

Table B.1 -- continued

BJ30 41°F

DURATION DAYS	OVEN			FD OVEN			UV		
	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #
0 DAY	BJ10	2.486	6750.0	423.50					
	BJ18	2.506	6750.0	420.17					
	AVG	2.496	6750.0	421.83					
14 DAYS	BJ24	2.494	7400.0	462.85	BJ27	2.506	6700.0	416.95	BJ16
	BJ57	2.533	6950.0	427.95	BJ56	2.524	7500.0	463.53	BJ29
	AVG	2.513	7175.0	445.40	AVG	2.515	7100.0	440.24	AVG
28 DAYS	BJ22	2.505	6725.0	418.67	BJ07	2.476	7250.0	456.70	BJ40
	BJ37	2.536	7350.0	452.11	BJ11	2.502	7525.0	469.04	BJ54
	AVG	2.521	7037.5	435.39	AVG	2.489	7387.5	462.87	AVG
90 DAYS	BJ06	2.506	5125.0	319.02	BJ20	2.508	7025.0	436.88	BJ31
	BJ08	2.496	5075.0	317.13	BJ26	2.504	6975.0	434.41	BJ50
	AVG	2.501	5100.0	318.07	AVG	2.506	7000.0	435.65	AVG

Table B.1 -- continued

CT30 41°F

DURATION		OVEN			FD OVEN			HT			UV		
DAYS	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	
0 DAY	CT17	2.544	6000.0	367.81									
	CT24	2.562	5500.0	334.79									
	AVG	2.553	5750.0	351.30									
14 DAYS	CT03	2.528	6750.0	416.40	CT08	2.547	6750.0	413.41	CT19	2.550	6950.0	425.04	
	CT28	2.544	6000.0	367.81	CT12	2.541	6900.0	423.54	CT20	2.545	7000.0	429.06	
	AVG	2.536	6375.0	392.11	AVG	2.544	6825.0	418.47	AVG	2.548	6975.0	427.05	
28 DAYS	CT13	2.554	7000.0	427.54	CT02	2.515	6750.0	418.56	CT34	2.547	6550.0	401.16	
	CT14	2.543	6625.0	406.39	CT23	2.562	6800.0	414.03	CT47	2.548	6975.0	426.91	
	AVG	2.548	6812.5	416.97	AVG	2.539	6775.0	416.29	AVG	2.548	6762.5	414.03	
90 DAYS	CT21	2.541	6275.0	385.22	CT04	2.548	6525.0	399.42	CT42	2.520	6825.0	422.37	
	CT22	2.511	6825.0	423.88	CT33	2.521	7125.0	440.88	CT55	2.561	7200.0	438.44	
	AVG	2.526	6550.0	404.55	AVG	2.534	6825.0	420.15	AVG	2.541	7012.5	430.41	

Table B.1 -- continued

CT30 77°F

DURATION		OVEN			FD OVEN			HT			UV		
DAYS	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	
0 DAY	CT07	2.562	2250.0	136.98									
	CT26	2.524	2437.5	150.61									
	AVG	2.543	2343.8	143.79									
14 DAYS	CT11	2.537	2400.0	147.55	CT18	2.548	2725.0	166.83	CT46	2.539	2750.0	168.91	
	CT29	2.533	2262.5	139.30	CT30	2.557	2762.5	168.48	CT53	2.533	2675.0	164.74	
	AVG	2.535	2331.3	143.42	AVG	2.553	2743.8	167.66	AVG	2.536	2712.5	166.82	
28 DAYS	CT06	2.551	3062.5	187.25	CT10	2.534	2937.5	180.83	CT36	2.526	3000.0	185.24	
	CT15	2.541	3187.5	195.63	CT25	2.542	3000.0	184.10	CT40	2.532	2875.0	177.12	
	AVG	2.546	3125.0	191.44	AVG	2.538	2968.8	182.46	AVG	2.529	2937.5	181.18	
90 DAYS	CT01	2.526	3587.5	221.49	CT09	2.526	3687.5	227.66	CT31	2.548	3225.0	197.44	
	CT05	2.539	3475.0	213.44	CT27	2.539	3637.5	223.42	CT38	2.528	3375.0	208.26	
	AVG	2.533	3531.3	217.46	AVG	2.533	3662.5	225.54	AVG	2.538	3300.0	202.85	

Table B.1 -- continued

MT30 41°F

DURATION		OVEN			FD OVEN			SPEC			HT			UV		
DAYS	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)				
0 DAY	MT21	2.555	6250.0	381.49												
	MT30	2.548	6700.0	410.13												
	AVG	2.552	6475.0	395.81												
14 DAYS	MT18	2.541	7125.0	437.29	MT08	2.543	7025.0	430.81	MT05	2.542	7275.0	446.32				
	MT29	2.517	6975.0	432.28	MT20	2.533	7250.0	446.48	MT09	2.533	6900.0	424.82				
	AVG	2.529	7050.0	434.78	AVG	2.538	7137.5	438.65	AVG	2.538	7087.5	435.57				
28 DAYS	MT01	2.529	6425.0	396.30	MT17	2.535	7000.0	430.63	MT39	2.543	7350.0	450.80				
	MT23	2.545	6875.0	421.34	MT27	2.539	7200.0	442.36	MT57	2.558	6900.0	420.67				
	AVG	2.537	6650.0	408.82	AVG	2.537	7100.0	436.50	AVG	2.551	7125.0	435.74				
90 DAYS	MT06	2.537	6500.0	399.61	MT22	2.540	6625.0	406.87	MT43	2.558	7375.0	449.63				
	MT11	2.536	7300.0	448.91	MT59	2.549	7225.0	442.09	MT51	2.547	7275.0	445.56				
	AVG	2.537	6900.0	424.26	AVG	2.544	6925.0	424.48	AVG	2.553	7325.0	447.59				

Table B.1 -- continued

MT30 77°F

DURATION		OVEN			FD OVEN			UV				
DAYS	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)
0 DAY	MT10	2.537	2775.0	170.60								
	MT25	2.543	2750.0	168.69								
	AVG	2.540	2762.5	169.65								
14 DAYS	MT24	2.541	2750.0	168.80	MT03	2.538	3025.0	185.88	MT56	2.551	2962.5	181.16
	MT53	2.571	2750.0	166.85	MT16	2.545	3100.0	189.99	MT60	2.555	2875.0	175.51
	AVG	2.556	2750.0	167.83	AVG	2.542	3062.5	187.93	AVG	2.553	2918.8	178.33
28 DAYS	MT14	2.535	3562.5	219.22	MT02	2.505	3375.0	210.17	MT35	2.533	3350.0	206.31
	MT26	2.546	3550.0	217.45	MT45	2.548	3250.0	198.97	MT42	2.545	2950.0	180.77
	AVG	2.541	3556.3	218.33	AVG	2.526	3312.5	204.57	AVG	2.539	3150.0	193.54
90 DAYS	MT12	2.532	4250.0	261.84	MT15	2.539	3787.5	232.64	MT07	2.542	3875.0	237.73
	MT52	2.561	3750.0	228.36	MT28	2.528	3900.0	240.62	MT47	2.559	3512.5	214.09
	AVG	2.547	4000.0	245.10	AVG	2.534	3843.8	236.63	AVG	2.551	3693.8	225.91

Table B.2 Results of Resilient Modulus Test

MA30 41°F								
DURATION	SPEC	HT	OVEN				RESILIENT	RESILIENT
DAYS	#	(inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	MA15	2.539	8.20	8.00	8.20	8.00	301430.34	301430.34
	MA21	2.509	9.20	8.00	9.20	8.00	287375.86	287375.86
	AVG	2.524	8.70	8.00	8.70	8.00	294403.10	294403.10
14 DAYS	MA11	2.528	4.90	8.70	4.90	8.70	360618.87	360618.87
	MA24	2.521	6.20	7.80	6.20	7.80	351288.06	351288.06
	AVG	2.525	5.55	8.25	5.55	8.25	355953.46	355953.46
28 DAYS	MA19	2.537	7.80	8.30	7.80	8.30	303541.65	303541.65
	MA29	2.548	8.60	9.70	8.60	9.70	265897.57	265897.57
	AVG	2.543	8.20	9.00	8.20	9.00	284719.61	284719.61
90 DAYS	MA06	2.536	6.40	7.20	6.40	7.20	359528.67	359528.67
	MA25	2.557	7.00	7.50	7.00	7.50	334443.65	334443.65
	AVG	2.547	6.70	7.35	6.70	7.35	346986.16	346986.16

MA30 77°F								
DURATION	SPEC	HT	OVEN				RESILIENT	RESILIENT
DAYS	#	(inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	MA23	2.523	8.80	10.40	10.00	11.80	255944.52	225419.02
	MA30	2.547	9.00	9.50	10.30	11.00	263195.13	228596.71
	AVG	2.535	8.90	9.95	10.15	11.40	259569.83	227007.87
14 DAYS	MA08	2.539	9.50	10.10	10.50	11.10	249174.11	226102.43
	MA16	2.547	10.00	9.00	11.00	9.50	256201.88	237455.40
	AVG	2.543	9.75	9.55	10.75	10.30	252687.99	231778.91
28 DAYS	MA07	2.543	7.50	7.00	8.30	7.50	336284.87	308615.86
	MA17	2.534	8.00	8.00	8.70	8.30	305800.34	287812.09
	AVG	2.539	7.75	7.50	8.50	7.90	321042.60	298213.97
90 DAYS	MA01	2.508	7.90	7.40	7.90	7.50	323105.99	321007.90
	MA13	2.534	7.80	6.80	7.80	6.80	335123.66	335123.66
	AVG	2.521	7.85	7.10	7.85	7.15	329114.82	328065.78

Table B.2 -- continued

MA30 41°F

DURATION			FD				RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	MA15	2.539	8.20	8.00	8.20	8.00	301430.34	301430.34
	MA21	2.509	9.20	8.00	9.20	8.00	287375.86	287375.86
	AVG	2.524	8.70	8.00	8.70	8.00	294403.10	294403.10
14 DAYS	MA02	2.506	7.80	7.20	7.80	7.20	329874.97	329874.97
	MA18	2.522	6.50	8.00	6.50	8.00	339085.02	339085.02
	AVG	2.514	7.15	7.60	7.15	7.60	334479.99	334479.99
28 DAYS	MA04	2.518	6.80	7.90	6.80	7.90	335047.30	335047.30
	MA27	2.525	8.00	8.00	8.00	8.00	306971.22	306971.22
	AVG	2.521	7.40	7.95	7.40	7.95	321009.26	321009.26
90 DAYS	MA09	2.523	7.20	9.20	7.20	9.20	299642.36	299642.36
	MA10	2.547	8.00	7.90	8.00	7.90	306193.25	306193.25
	AVG	2.535	7.60	8.55	7.60	8.55	302917.81	302917.81

MA30 77°F

DURATION			FD				RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	MA23	2.523	8.80	10.40	10.00	11.80	255944.52	225419.02
	MA30	2.547	9.00	9.50	10.30	11.00	263195.13	228596.71
	AVG	2.535	8.90	9.95	10.15	11.40	259569.83	227007.87
14 DAYS	MA12	2.556	8.20	9.00	9.10	9.40	282090.87	262268.27
	MA20	2.505	9.20	8.70	10.00	9.70	276578.69	251307.54
	AVG	2.530	8.70	8.85	9.55	9.55	279334.78	256787.91
28 DAYS	MA05	2.518	7.20	10.00	7.80	10.90	286348.56	263379.43
	MA22	2.519	8.10	8.20	8.90	9.00	301959.33	274968.55
	AVG	2.519	7.65	9.10	8.35	9.95	294153.94	269173.99
90 DAYS	MA14	2.527	8.50	7.80	8.90	8.00	301043.21	290355.29
	MA26	2.549	9.50	8.60	10.20	8.80	268800.50	256067.84
	AVG	2.538	9.00	8.20	9.55	8.40	284921.86	273211.57

Table B.2 -- continued

MA30 41°F

DURATION			UV				RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	MA15	2.539	8.20	8.00	8.20	8.00	301430.34	301430.34
	MA21	2.509	9.20	8.00	9.20	8.00	287375.86	287375.86
	AVG	2.524	8.70	8.00	8.70	8.00	294403.10	294403.10
14 DAYS	MA03	2.540	7.50	9.50	7.50	9.50	287132.30	287132.30
	MA28	2.543	7.70	7.00	7.70	7.00	331666.09	331666.09
	AVG	2.542	7.60	8.25	7.60	8.25	309399.20	309399.20
28 DAYS	MA32	2.543	7.80	6.60	7.80	6.60	338664.57	338664.57
	MA35	2.516	7.60	7.10	7.60	7.10	335269.24	335269.24
	AVG	2.529	7.70	6.85	7.70	6.85	336966.91	336966.91
90 DAYS	MA31	2.552	9.30	7.50	9.30	7.50	289222.27	289222.27
	MA38	2.550	7.80	6.00	7.80	6.00	352418.90	352418.90
	AVG	2.551	8.55	6.75	8.55	6.75	320820.59	320820.59

MA30 77°F

DURATION			UV				RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	MA23	2.523	8.80	10.40	10.00	11.80	255944.52	225419.02
	MA30	2.547	9.00	9.50	10.30	11.00	263195.13	228596.71
	AVG	2.535	8.90	9.95	10.15	11.40	259569.83	227007.87
14 DAYS	MA39	2.540	10.00	8.80	10.80	10.00	259640.91	234675.44
	MA47	2.526	9.20	8.80	10.10	10.10	272719.28	243017.18
	AVG	2.533	9.60	8.80	10.45	10.05	266180.09	238846.31
28 DAYS	MA33	2.515	8.00	9.20	9.30	10.60	286614.19	247726.84
	MA58	2.535	9.00	9.00	9.80	9.90	271715.31	248267.80
	AVG	2.525	8.50	9.10	9.55	10.25	279164.75	247997.32
90 DAYS	MA48	2.525	8.50	9.10	9.00	9.80	279027.90	261217.61
	MA50	2.529	7.80	8.40	8.10	9.10	302661.96	285065.34
	AVG	2.527	8.15	8.75	8.55	9.45	290844.93	273141.47

Table B.2 -- continued

BF30 41°F

DURATION			OVEN				RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	BF05	2.538	7.20	10.50	7.20	10.50	276030.33	276030.33
	BF17	2.532	6.00	8.00	6.00	8.00	349808.17	349808.17
	AVG	2.535	6.60	9.25	6.60	9.25	312919.25	312919.25
14 DAYS	BF26	2.558	5.90	7.00	5.90	7.00	375778.07	375778.07
	BF34	2.537	7.30	5.80	7.30	5.80	373153.04	373153.04
	AVG	2.547	6.60	6.40	6.60	6.40	374465.56	374465.56
28 DAYS	BF03	2.535	9.30	8.00	9.30	8.00	282746.75	282746.75
	BF07	2.535	7.90	7.50	7.90	7.50	317672.86	317672.86
	AVG	2.535	8.60	7.75	8.60	7.75	300209.80	300209.80
90 DAYS	BF30	2.547	7.10	6.20	7.10	6.20	366002.68	366002.68
	BF51	2.554	7.60	7.90	7.60	7.90	313234.14	313234.14
	AVG	2.551	7.35	7.05	7.35	7.05	339618.41	339618.41

BF30 77°F

DURATION			OVEN				RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	BF06	2.537	10.10	9.00	11.10	10.20	255864.95	229437.58
	BF18	2.553	8.50	8.80	9.70	9.80	280753.23	249078.51
	AVG	2.545	9.30	8.90	10.40	10.00	268309.09	239258.05
14 DAYS	BF02	2.542	9.20	9.00	10.10	9.60	267989.52	247584.22
	BF04	2.531	9.00	8.00	9.50	9.00	288191.14	264824.29
	AVG	2.537	9.10	8.50	9.80	9.30	278090.33	256204.26
28 DAYS	BF15	2.556	11.20	9.00	11.50	9.60	240133.55	229890.88
	BF29	2.537	9.00	10.00	9.80	10.50	257245.40	240771.56
	AVG	2.547	10.10	9.50	10.65	10.05	248689.47	235331.22
90 DAYS	BF11	2.528	8.40	8.00	8.60	8.30	299089.23	290240.43
	BF14	2.528	8.00	7.90	8.30	8.40	308535.23	293755.10
	AVG	2.528	8.20	7.95	8.45	8.35	303812.23	291997.76

Table B.2 -- continued

BF30 41°F

DURATION					FD		RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	BF05	2.538	7.20	10.50	7.20	10.50	276030.33	276030.33
	BF17	2.532	6.00	8.00	6.00	8.00	349808.17	349808.17
	AVG	2.535	6.60	9.25	6.60	9.25	312919.25	312919.25
14 DAYS	BF08	2.535	9.20	7.60	9.20	7.60	291200.12	291200.12
	BF27	2.557	8.50	6.80	8.50	6.80	316997.72	316997.72
	AVG	2.546	8.85	7.20	8.85	7.20	304098.92	304098.92
28 DAYS	BF13	2.538	8.80	8.60	8.80	8.60	280826.35	280826.35
	BF47	2.526	8.00	7.30	8.20	7.70	320888.55	308779.55
	AVG	2.532	8.40	7.95	8.50	8.15	300857.45	294802.95
90 DAYS	BF24	2.552	6.80	7.00	6.80	7.00	352096.68	352096.68
	BF54	2.571	6.60	7.10	6.60	7.10	352091.35	352091.35
	AVG	2.561	6.70	7.05	6.70	7.05	352094.01	352094.01

BF30 77°F

DURATION					FD		RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	BF06	2.537	10.10	9.00	11.10	10.20	255864.95	229437.58
	BF18	2.553	8.50	8.80	9.70	9.80	280753.23	249078.51
	AVG	2.545	9.30	8.90	10.40	10.00	268309.09	239258.05
14 DAYS	BF10	2.536	9.10	8.50	9.80	9.40	277817.61	254666.14
	BF57	2.536	9.00	9.40	9.20	10.00	265738.58	254666.14
	AVG	2.536	9.05	8.95	9.50	9.70	271778.10	254666.14
28 DAYS	BF20	2.527	10.00	8.00	10.80	8.60	272611.35	252938.37
	BF23	2.549	7.60	9.20	8.00	9.90	289524.81	271732.78
	AVG	2.538	8.80	8.60	9.40	9.25	281068.08	262335.57
90 DAYS	BF01	2.532	9.00	8.50	9.90	8.90	279883.38	260529.74
	BF16	2.538	7.40	7.40	8.00	8.00	330074.00	305318.45
	AVG	2.535	8.20	7.95	8.95	8.45	304978.69	282924.10

Table B.2 -- continued

BF30 41°F								
DURATION	SPEC	HT	UV				RESILIENT	RESILIENT
DAYS	#	(inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	BF05	2.538	7.20	10.50	7.20	10.50	276030.33	276030.33
	BF17	2.532	6.00	8.00	6.00	8.00	349808.17	349808.17
	AVG	2.535	6.60	9.25	6.60	9.25	312919.25	312919.25
14 DAYS	BF22	2.523	6.50	8.40	6.50	8.40	329894.86	329894.86
	BF41	2.539	6.50	8.00	6.50	8.00	336858.88	336858.88
	AVG	2.531	6.50	8.20	6.50	8.20	333376.87	333376.87
28 DAYS	BF33	2.517	8.30	7.60	8.30	7.60	309842.75	309842.75
	BF46	2.522	7.90	7.00	8.00	7.00	329938.46	327738.87
	AVG	2.520	8.10	7.30	8.15	7.30	319890.61	318790.81
90 DAYS	BF12	2.534	7.60	6.50	7.60	6.50	347098.79	347098.79
	BF40	2.529	7.60	8.50	7.60	8.50	304501.71	304501.71
	AVG	2.532	7.60	7.50	7.60	7.50	325800.25	325800.25

BF30 77°F								
DURATION	SPEC	HT	UV				RESILIENT	RESILIENT
DAYS	#	(inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	BF06	2.537	10.10	9.00	11.10	10.20	255864.95	229437.58
	BF18	2.553	8.50	8.80	9.70	9.80	280753.23	249078.51
	AVG	2.545	9.30	8.90	10.40	10.00	268309.09	239258.05
14 DAYS	BF32	2.552	8.50	9.00	9.20	9.50	277689.65	259870.00
	BF44	2.552	7.60	9.00	8.40	9.80	292668.65	266939.54
	AVG	2.552	8.05	9.00	8.80	9.65	285179.15	263404.77
28 DAYS	BF48	2.543	8.10	8.20	9.10	9.00	299149.11	269399.48
	BF55	2.553	8.20	8.00	9.40	8.60	299777.58	269799.83
	AVG	2.548	8.15	8.10	9.25	8.80	299463.35	269599.65
90 DAYS	BF39	2.549	8.00	8.30	8.20	8.40	298405.93	293013.06
	BF50	2.546	8.20	7.90	8.40	8.10	302468.78	295136.20
	AVG	2.548	8.10	8.10	8.30	8.25	300437.36	294074.63

Table B.2 -- continued

BJ30 41°F

DURATION		SPEC #	HT (inch)	OVEN			RESILIENT MODULUS IR(psi)	RESILIENT MODULUS TR(psi)
DAYS				IR(A)	IR(B)	TR(A)	TR(B)	
0 DAY	BJ10	2.486	8.50	7.50	8.50	7.50	311745.78	311745.78
	BJ18	2.506	7.20	8.10	7.20	8.10	323449.85	323449.85
	AVG	2.496	7.85	7.80	7.85	7.80	317597.81	317597.81
14 DAYS	BJ24	2.494	8.00	7.60	8.00	7.60	318756.23	318756.23
	BJ57	2.533	9.80	7.80	9.80	7.80	278146.65	278146.65
	AVG	2.513	8.90	7.70	8.90	7.70	298451.44	298451.44
28 DAYS	BJ22	2.505	8.20	9.60	8.20	9.60	278058.49	278058.49
	BJ37	2.536	8.90	6.60	8.90	6.60	315498.88	315498.88
	AVG	2.521	8.55	8.10	8.55	8.10	296778.69	296778.69
90 DAYS	BJ06	2.506	9.30	7.00	9.30	7.00	303606.30	303606.30
	BJ08	2.496	7.00	8.00	7.00	8.00	331196.58	331196.58
	AVG	2.501	8.15	7.50	8.15	7.50	317401.44	317401.44

BJ30 77°F

DURATION		SPEC #	HT (inch)	OVEN			RESILIENT MODULUS IR(psi)	RESILIENT MODULUS TR(psi)
DAYS				IR(A)	IR(B)	TR(A)	TR(B)	
0 DAY	BJ14	2.504	11.00	10.00	12.30	11.00	235781.79	212507.19
	BJ28	2.521	10.20	8.80	11.30	9.80	258912.29	233143.77
	AVG	2.513	10.60	9.40	11.80	10.40	247347.04	222825.48
14 DAYS	BJ01	2.488	10.00	11.50	11.60	13.00	231779.31	202571.35
	BJ30	2.488	10.00	8.60	11.00	9.50	267916.95	243085.62
	AVG	2.488	10.00	10.05	11.30	11.25	249848.13	222828.48
28 DAYS	BJ02	2.502	8.20	7.50	8.50	8.20	315628.98	296729.04
	BJ13	2.491	9.00	10.00	9.20	10.40	262030.88	254009.53
	AVG	2.497	8.60	8.75	8.85	9.30	288829.93	275369.28
90 DAYS	BJ15	2.510	8.50	8.00	8.80	8.40	299368.67	287185.06
	BJ25	2.535	8.80	8.00	9.00	8.00	291200.12	287774.24
	AVG	2.523	8.65	8.00	8.90	8.20	295284.40	287479.65

Table B.2 -- continued

BJ30 41°F

DURATION			FD				RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	BJ10	2.486	8.50	7.50	8.50	7.50	311745.78	311745.78
	BJ18	2.506	7.20	8.10	7.20	8.10	323449.85	323449.85
	AVG	2.496	7.85	7.80	7.85	7.80	317597.81	317597.81
14 DAYS	BJ27	2.506	8.30	8.30	8.30	8.30	298040.15	298040.15
	BJ56	2.524	8.00	9.10	8.00	9.10	287338.34	287338.34
	AVG	2.515	8.15	8.70	8.15	8.70	292689.24	292689.24
28 DAYS	BJ07	2.476	6.40	9.50	6.40	9.50	314973.43	314973.43
	BJ11	2.502	7.80	7.80	8.00	8.00	317652.24	309710.94
	AVG	2.489	7.10	8.65	7.20	8.75	316312.84	312342.18
90 DAYS	BJ20	2.508	8.10	7.80	8.10	7.80	310954.63	310954.63
	BJ26	2.504	8.00	5.80	8.00	5.80	358798.37	358798.37
	AVG	2.506	8.05	6.80	8.05	6.80	334876.50	334876.50

BJ30 77°F

DURATION			FD				RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	BJ14	2.504	11.00	10.00	12.30	11.00	235781.79	212507.19
	BJ28	2.521	10.20	8.80	11.30	9.80	258912.29	233143.77
	AVG	2.513	10.60	9.40	11.80	10.40	247347.04	222825.48
14 DAYS	BJ09	2.506	8.90	8.40	9.70	9.00	285980.72	264570.40
	BJ17	2.498	8.70	7.50	9.30	8.20	306458.87	283693.35
	AVG	2.502	8.80	7.95	9.50	8.60	296219.79	274131.87
28 DAYS	BJ03	2.500	6.20	9.20	7.00	9.70	322120.87	297045.59
	BJ23	2.511	8.20	9.10	8.60	9.90	285449.23	266933.60
	AVG	2.505	7.20	9.15	7.80	9.80	303785.05	281989.60
90 DAYS	BJ04	2.474	8.20	8.50	8.80	8.90	300086.88	283132.82
	BJ12	2.494	9.40	8.60	9.70	8.80	276255.40	268789.04
	AVG	2.484	8.80	8.55	9.25	8.85	288171.14	275960.93

Table B.2 -- continued

BJ30 41°F

DURATION		SPEC #	HT (inch)	UV				RESILIENT MODULUS IR(psi)	RESILIENT MODULUS TR(psi)
DAYS				IR(A)	IR(B)	TR(A)	TR(B)		
0 DAY	BJ10	2.486	8.50	7.50	8.50	7.50	7.50	311745.78	311745.78
	BJ18	2.506	7.20	8.10	7.20	8.10	8.10	323449.85	323449.85
	AVG	2.496	7.85	7.80	7.85	7.80	7.80	317597.81	317597.81
14 DAYS	BJ16	2.491	7.20	7.90	7.20	7.90	7.90	329663.61	329663.61
	BJ29	2.497	8.80	8.80	8.80	8.80	8.80	282156.77	282156.77
	AVG	2.494	8.00	8.35	8.00	8.35	8.35	305910.19	305910.19
28 DAYS	BJ40	2.496	6.30	7.70	6.30	7.80	7.80	354806.10	352289.74
	BJ54	2.535	8.00	6.80	8.00	6.90	6.90	330551.49	328333.02
	AVG	2.516	7.15	7.25	7.15	7.35	7.35	342678.79	340311.38
90 DAYS	BJ31	2.501	7.60	7.60	7.60	7.80	7.80	326185.32	321949.14
	BJ50	2.510	8.00	7.80	8.00	7.80	7.80	312714.89	312714.89
	AVG	2.505	7.80	7.70	7.80	7.80	7.80	319450.10	317332.01

BJ30 77°F

DURATION		SPEC #	HT (inch)	UV				RESILIENT MODULUS IR(psi)	RESILIENT MODULUS TR(psi)
DAYS				IR(A)	IR(B)	TR(A)	TR(B)		
0 DAY	BJ14	2.504	11.00	10.00	12.30	11.00	11.00	235781.79	212507.19
	BJ28	2.521	10.20	8.80	11.30	9.80	9.80	258912.29	233143.77
	AVG	2.513	10.60	9.40	11.80	10.40	10.40	247347.04	222825.48
14 DAYS	BJ19	2.496	8.80	10.00	9.50	11.00	11.00	264217.31	242306.60
	BJ36	2.535	9.20	11.00	9.90	11.60	11.60	242122.56	227482.59
	AVG	2.516	9.00	10.50	9.70	11.30	11.30	253169.93	234894.59
28 DAYS	BJ45	2.505	9.00	9.60	9.50	10.60	10.60	266098.99	246240.86
	BJ47	2.501	6.00	9.30	6.90	10.10	10.10	324096.58	291686.92
	AVG	2.503	7.50	9.45	8.20	10.35	10.35	295097.78	268963.89
90 DAYS	BJ34	2.509	6.80	7.80	7.00	8.40	8.40	338507.40	320922.60
	BJ59	2.524	7.60	7.70	7.90	7.90	7.90	321058.04	310897.98
	AVG	2.517	7.20	7.75	7.45	8.15	8.15	329782.72	315910.29

Table B.2 -- continued

CT30 41°F

DURATION		HT (inch)	OVEN				RESILIENT MODULUS IR(psi)	RESILIENT MODULUS TR(psi)
DAYS	SPEC #		IR(A)	IR(B)	TR(A)	TR(B)		
0 DAY	CT17	2.544	8.80	8.80	8.80	8.80	276907.69	276907.69
	CT24	2.562	7.50	9.00	7.50	9.00	293293.28	293293.28
	AVG	2.553	8.15	8.90	8.15	8.90	285100.48	285100.48
14 DAYS	CT03	2.528	6.50	4.50	6.50	4.50	445856.06	445856.06
	CT28	2.544	6.00	9.00	6.00	9.00	324905.02	324905.02
	AVG	2.536	6.25	6.75	6.25	6.75	385380.54	385380.54
28 DAYS	CT13	2.554	7.40	8.20	7.40	8.20	311266.86	311266.86
	CT14	2.543	7.80	7.10	7.80	7.10	327299.99	327299.99
	AVG	2.548	7.60	7.65	7.60	7.65	319283.42	319283.42
90 DAYS	CT21	2.541	6.90	7.10	6.90	7.10	348614.91	348614.91
	CT22	2.511	7.20	8.20	7.20	8.20	320624.42	320624.42
	AVG	2.526	7.05	7.65	7.05	7.65	334619.67	334619.67

CT30 77°F

DURATION		HT (inch)	OVEN				RESILIENT MODULUS IR(psi)	RESILIENT MODULUS TR(psi)
DAYS	SPEC #		IR(A)	IR(B)	TR(A)	TR(B)		
0 DAY	CT07	2.562	10.00	10.00	11.00	11.50	241998.44	215109.72
	CT26	2.524	9.30	9.50	10.20	11.00	261286.60	231706.98
	AVG	2.543	9.65	9.75	10.60	11.25	251642.52	223408.35
14 DAYS	CT11	2.537	9.70	10.00	10.50	11.20	248104.70	225237.91
	CT29	2.533	10.50	9.00	11.30	10.10	251012.15	228726.02
	AVG	2.535	10.10	9.50	10.90	10.65	249558.42	226981.96
28 DAYS	CT06	2.551	9.60	8.50	10.40	9.00	268554.63	250558.71
	CT15	2.541	9.00	9.60	9.80	10.00	262329.49	246430.73
	AVG	2.546	9.30	9.05	10.10	9.50	265442.06	248494.72
90 DAYS	CT01	2.526	9.40	8.50	10.00	8.90	274206.66	259698.37
	CT05	2.539	8.70	7.80	9.40	8.50	295949.78	272802.87
	AVG	2.533	9.05	8.15	9.70	8.70	285078.22	266250.62

Table B.2 -- continued

CT30 41°F

DURATION		SPEC #	HT (inch)	FD				RESILIENT MODULUS IR(psi)	RESILIENT MODULUS TR(psi)
DAYS				IR(A)	IR(B)	TR(A)	TR(B)		
0 DAY	CT17	2.544	8.80	8.80	8.80	8.80	8.80	276907.69	276907.69
	CT24	2.562	7.50	9.00	7.50	9.00	9.00	293293.28	293293.28
	AVG	2.553	8.15	8.90	8.15	8.90	8.90	285100.48	285100.48
14 DAYS	CT08	2.547	7.50	8.20	8.00	8.20	8.20	310134.39	300562.34
	CT12	2.541	7.60	8.00	7.60	8.00	8.00	312818.49	312818.49
	AVG	2.544	7.55	8.10	7.80	8.10	8.10	311476.44	306690.42
28 DAYS	CT02	2.515	9.60	7.60	9.60	7.60	7.60	286614.19	286614.19
	CT23	2.562	8.00	8.10	8.30	8.10	8.10	300658.30	295158.45
	AVG	2.539	8.80	7.85	8.95	7.85	7.85	293636.24	290886.32
90 DAYS	CT04	2.548	9.70	7.60	9.70	7.60	7.60	281304.16	281304.16
	CT33	2.521	8.80	9.30	8.80	9.30	9.30	271786.38	271786.38
	AVG	2.534	9.25	8.45	9.25	8.45	8.45	276545.27	276545.27

CT30 77°F

DURATION		SPEC #	HT (inch)	FD				RESILIENT MODULUS IR(psi)	RESILIENT MODULUS TR(psi)
DAYS				IR(A)	IR(B)	TR(A)	TR(B)		
0 DAY	CT07	2.562	10.00	10.00	11.00	11.00	11.50	241998.44	215109.72
	CT26	2.524	9.30	9.50	10.20	11.00	11.00	261286.60	231706.98
	AVG	2.543	9.65	9.75	10.60	11.25	11.25	251642.52	223408.35
14 DAYS	CT18	2.548	8.50	9.20	9.00	10.10	10.10	274982.98	254827.16
	CT30	2.557	6.90	8.70	7.60	9.30	9.30	310820.57	286911.29
	AVG	2.553	7.70	8.95	8.30	9.70	9.70	292901.77	270869.23
28 DAYS	CT10	2.534	8.00	9.10	8.60	9.60	9.60	286204.26	268906.20
	CT25	2.542	9.60	8.30	10.20	9.10	9.10	272552.43	252781.79
	AVG	2.538	8.80	8.70	9.40	9.35	9.35	279378.35	260844.00
90 DAYS	CT09	2.526	8.20	9.50	8.20	9.50	9.50	277305.04	277305.04
	CT27	2.539	8.80	9.80	9.00	9.80	9.80	262536.10	259743.16
	AVG	2.533	8.50	9.65	8.60	9.65	9.65	269920.57	268524.10

Table B.2 -- continued

CT30 41°F

DURATION					UV		RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	CT17	2.544	8.80	8.80	8.80	8.80	276907.69	276907.69
	CT24	2.562	7.50	9.00	7.50	9.00	293293.28	293293.28
	AVG	2.553	8.15	8.90	8.15	8.90	285100.48	285100.48
14 DAYS	CT19	2.550	5.40	9.00	5.40	9.00	337646.50	337646.50
	CT20	2.545	6.80	8.90	6.80	8.90	310378.14	310378.14
	AVG	2.548	6.10	8.95	6.10	8.95	324012.32	324012.32
28 DAYS	CT34	2.547	7.40	6.90	7.50	6.90	340497.20	338132.64
	CT47	2.548	7.60	7.20	7.60	7.20	328778.75	328778.75
	AVG	2.548	7.50	7.05	7.55	7.05	334637.97	333455.69
90 DAYS	CT42	2.520	7.60	7.50	7.60	8.00	325826.76	315383.60
	CT55	2.561	7.10	7.00	7.10	7.00	343349.54	343349.54
	AVG	2.541	7.35	7.25	7.35	7.50	334588.15	329366.57

CT30 77°F

DURATION					UV		RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	CT07	2.562	10.00	10.00	11.00	11.50	241998.44	215109.72
	CT26	2.524	9.30	9.50	10.20	11.00	261286.60	231706.98
	AVG	2.543	9.65	9.75	10.60	11.25	251642.52	223408.35
14 DAYS	CT46	2.539	9.00	10.00	10.00	11.20	257009.02	230338.28
	CT53	2.533	9.00	10.50	9.80	12.00	251078.22	224588.32
	AVG	2.536	9.00	10.25	9.90	11.60	254043.62	227463.30
28 DAYS	CT36	2.526	10.00	8.80	10.50	9.50	261114.20	245447.35
	CT40	2.532	9.00	10.00	9.20	10.50	257787.33	248627.37
	AVG	2.529	9.50	9.40	9.85	10.00	259450.76	247037.36
90 DAYS	CT31	2.548	7.20	10.20	7.80	10.60	279724.07	264521.67
	CT38	2.528	8.60	8.30	8.90	8.60	290278.71	280326.29
	AVG	2.538	7.90	9.25	8.35	9.60	285001.39	272423.98

Table B.2 -- continued

MT30 41°F

DURATION		SPEC #	HT (inch)	OVEN				RESILIENT MODULUS IR(psi)	RESILIENT MODULUS TR(psi)
DAYS				IR(A)	IR(B)	TR(A)	TR(B)		
0 DAY	MT21	2.555	8.00	8.10	8.00	8.10	8.10	301403.47	301403.47
	MT30	2.548	7.00	8.00	7.00	8.00	8.00	324437.47	324437.47
	AVG	2.552	7.50	8.05	7.50	8.05	8.05	312920.47	312920.47
14 DAYS	MT18	2.541	6.80	8.10	6.80	8.10	8.10	327471.71	327471.71
	MT29	2.517	5.50	5.10	5.50	5.10	5.10	464825.69	464825.69
	AVG	2.529	6.15	6.60	6.15	6.60	6.60	396148.70	396148.70
28 DAYS	MT01	2.529	8.00	7.00	8.00	7.00	7.00	326918.01	326918.01
	MT23	2.545	8.00	8.80	8.00	8.80	8.80	290017.78	290017.78
	AVG	2.537	8.00	7.90	8.00	7.90	7.90	308467.89	308467.89
90 DAYS	MT06	2.537	8.10	7.00	8.10	7.00	7.00	323686.26	323686.26
	MT11	2.536	7.00	7.90	7.00	7.90	7.90	328117.27	328117.27
	AVG	2.537	7.55	7.45	7.55	7.45	7.45	325901.77	325901.77

MT30 77°F

DURATION		SPEC #	HT (inch)	OVEN				RESILIENT MODULUS IR(psi)	RESILIENT MODULUS TR(psi)
DAYS				IR(A)	IR(B)	TR(A)	TR(B)		
0 DAY	MT10	2.537	9.00	9.00	10.00	10.10	10.10	271536.81	243167.29
	MT25	2.543	9.20	8.80	10.30	9.60	9.60	270931.66	245063.81
	AVG	2.540	9.10	8.90	10.15	9.85	9.85	271234.23	244115.55
14 DAYS	MT24	2.541	8.50	8.90	9.20	9.90	9.90	280457.96	255495.73
	MT53	2.571	9.00	10.00	9.90	10.70	10.70	253876.39	234157.84
	AVG	2.556	8.75	9.45	9.55	10.30	10.30	267167.18	244826.79
28 DAYS	MT14	2.535	9.50	8.50	10.20	8.80	8.80	271786.78	257482.21
	MT26	2.546	7.80	7.30	8.10	8.00	8.00	322499.82	302468.78
	AVG	2.541	8.65	7.90	9.15	8.40	8.40	297143.30	279975.50
90 DAYS	MT12	2.532	7.00	8.30	7.30	8.50	8.50	320128.05	309997.42
	MT52	2.561	8.00	8.50	8.60	9.20	9.20	293407.79	271979.13
	AVG	2.547	7.50	8.40	7.95	8.85	8.85	306767.92	290988.27

Table B.2 -- continued

MT30 41°F

DURATION			FD				RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	MT21	2.555	8.00	8.10	8.00	8.10	301403.47	301403.47
	MT30	2.548	7.00	8.00	7.00	8.00	324437.47	324437.47
	AVG	2.552	7.50	8.05	7.50	8.05	312920.47	312920.47
14 DAYS	MT08	2.543	7.00	7.00	7.00	7.00	348249.39	348249.39
	MT20	2.533	7.00	9.50	7.00	9.50	296728.80	296728.80
	AVG	2.538	7.00	8.25	7.00	8.25	322489.10	322489.10
28 DAYS	MT17	2.535	9.50	7.00	9.50	7.00	296416.70	296416.70
	MT27	2.539	7.70	9.70	7.70	9.70	280715.73	280715.73
	AVG	2.537	8.60	8.35	8.60	8.35	288566.22	288566.22
90 DAYS	MT22	2.540	6.50	7.60	6.50	7.60	346278.76	346278.76
	MT59	2.549	8.20	7.80	8.20	7.80	304040.80	304040.80
	AVG	2.544	7.35	7.70	7.35	7.70	325159.78	325159.78

MT30 77°F

DURATION			FD				RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	MT10	2.537	9.00	9.00	10.00	10.10	271536.81	243167.29
	MT25	2.543	9.20	8.80	10.30	9.60	270931.66	245063.81
	AVG	2.540	9.10	8.90	10.15	9.85	271234.23	244115.55
14 DAYS	MT03	2.538	9.00	9.20	9.20	10.00	268411.82	254432.04
	MT16	2.545	9.50	9.00	10.10	9.40	263367.49	249861.47
	AVG	2.542	9.25	9.10	9.65	9.70	265889.66	252146.75
28 DAYS	MT02	2.505	8.40	11.40	9.20	12.00	250038.31	233526.35
	MT45	2.548	10.00	8.40	10.20	8.80	264521.67	256168.35
	AVG	2.526	9.20	9.90	9.70	10.40	257279.99	244847.35
90 DAYS	MT15	2.539	9.40	7.20	9.70	7.20	294166.95	288945.06
	MT28	2.528	7.50	8.30	8.20	8.50	310447.04	293716.36
	AVG	2.534	8.45	7.75	8.95	7.85	302307.00	291330.71

Table B.2 -- continued

MT30 41°F

DURATION			UV				RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	MT21	2.555	8.00	8.10	8.00	8.10	301403.47	301403.47
	MT30	2.548	7.00	8.00	7.00	8.00	324437.47	324437.47
	AVG	2.552	7.50	8.05	7.50	8.05	312920.47	312920.47
14 DAYS	MT05	2.542	8.00	7.50	8.00	7.50	314671.56	314671.56
	MT09	2.533	7.20	8.20	7.20	8.20	317840.05	317840.05
	AVG	2.538	7.60	7.85	7.60	7.85	316255.81	316255.81
28 DAYS	MT39	2.543	6.00	6.40	6.00	6.40	393236.34	393236.34
	MT57	2.558	7.00	6.90	7.00	6.90	348698.24	348698.24
	AVG	2.551	6.50	6.65	6.50	6.65	370967.29	370967.29
90 DAYS	MT43	2.558	7.30	7.50	7.30	7.50	327493.62	327493.62
	MT51	2.547	7.90	7.80	7.90	7.80	310134.39	310134.39
	AVG	2.553	7.60	7.65	7.60	7.65	318814.00	318814.00

MT30 77°F

DURATION			UV				RESILIENT	RESILIENT
DAYS	SPEC #	HT (inch)	IR(A)	IR(B)	TR(A)	TR(B)	MODULUS IR(psi)	MODULUS TR(psi)
0 DAY	MT10	2.537	9.00	9.00	10.00	10.10	271536.81	243167.29
	MT25	2.543	9.20	8.80	10.30	9.60	270931.66	245063.81
	AVG	2.540	9.10	8.90	10.15	9.85	271234.23	244115.55
14 DAYS	MT56	2.551	9.20	8.00	10.20	8.60	282643.84	258589.05
	MT60	2.555	9.00	9.50	10.30	9.60	262336.70	243880.85
	AVG	2.553	9.10	8.75	10.25	9.10	272490.27	251234.95
28 DAYS	MT35	2.533	10.00	8.00	11.60	9.10	272001.40	236522.96
	MT42	2.545	9.40	8.00	10.20	9.50	279980.49	247292.41
	AVG	2.539	9.70	8.00	10.90	9.30	275990.95	241907.69
90 DAYS	MT07	2.542	6.80	9.20	6.90	9.40	304838.08	299227.56
	MT47	2.559	9.00	8.20	9.00	8.40	281723.42	278485.22
	AVG	2.551	7.90	8.70	7.95	8.90	293280.75	288856.39

Table B.3 Results of Fracture Energy

41°F OVEN		ENERGY (Pascal)		77°F OVEN		ENERGY (Pascal)
0 DAY	MA15	4688.054		0 DAY	MA23	2969.486
	MA21	4095.136			MA30	2829.140
14 DAYS	MA11	4316.547		14 DAYS	MA08	2517.752
	MA24	3950.295			MA16	2661.722
28 DAYS	MA19	4713.207		28 DAYS	MA07	4077.282
	MA29	4992.910			MA17	3964.058
90 DAYS	MA06	2072.272		90 DAYS	MA01	3973.599
	MA25	2836.619			MA13	3883.461
0 DAY	BF05	4292.911		0 DAY	BF06	3007.080
	BF17	4189.824			BF18	3612.130
14 DAYS	BF26	4240.442		14 DAYS	BF02	3364.573
	BF34	2547.131			BF04	3719.821
28 DAYS	BF03	3928.731		28 DAYS	BF15	4846.185
	BF07	4564.332			BF29	4539.206
90 DAYS	BF30	2499.559		90 DAYS	BF11	3781.089
	BF51	4089.911			BF14	4900.945
0 DAY	MT21	2876.584		0 DAY	MT10	3384.909
	MT30	3638.728			MT25	3425.246
14 DAYS	MT18	1779.824		14 DAYS	MT24	2895.605
	MT29	1879.641			MT53	2898.826
28 DAYS	MT01	2858.506		28 DAYS	MT14	4667.066
	MT23	3790.381			MT26	4624.831
90 DAYS	MT06	3871.781		90 DAYS	MT12	4543.024
	MT11	4347.732			MT52	3598.001
0 DAY	BJ10	3909.448		0 DAY	BJ14	3213.476
	BJ18	4281.770			BJ28	2567.324
14 DAYS	BJ24	3252.853		14 DAYS	BJ01	2055.635
	BJ57	2718.906			BJ30	3146.547
28 DAYS	BJ22	4239.550		28 DAYS	BJ02	4230.037
	BJ37	4346.475			BJ13	4560.782
90 DAYS	BJ06	2363.240		90 DAYS	BJ15	3216.303
	BJ08	1986.252			BJ25	3794.693
0 DAY	CT17	5488.819		0 DAY	CT07	2544.780
	CT24	4237.362			CT26	2711.963
14 DAYS	CT03	2495.203		14 DAYS	CT11	2671.963
	CT28	1854.417			CT29	2145.203
28 DAYS	CT13	3994.037		28 DAYS	CT06	3404.181
	CT14	3719.378			CT15	3301.757
90 DAYS	CT21	3397.528		90 DAYS	CT01	3021.378
	CT22	4015.849			CT05	2869.339

Table B.3 -- continued

41'F FD		ENERGY (Pascal)	77'F FD		ENERGY (Pascal)
0 DAY	MA15	4688.054	0 DAY	MA23	2969.486
	MA21	4095.136		MA30	2829.140
14 DAYS	MA02	5818.114	14 DAYS	MA12	3011.978
	MA18	3833.798		MA20	3153.220
28 DAYS	MA04	4467.894	28 DAYS	MA05	3130.762
	MA27	4795.293		MA22	1348.549
90 DAYS	MA09	4564.796	90 DAYS	MA14	3921.362
	MA10	4859.562		MA26	3273.385
0 DAY	BF05	4292.911	0 DAY	BF06	3007.080
	BF17	4189.824		BF18	3612.130
14 DAYS	BF08	4211.013	14 DAYS	BF10	3908.313
	BF27	4766.229		BF57	3655.346
28 DAYS	BF13	6628.576	28 DAYS	BF20	3604.864
	BF47	4521.085		BF23	3794.648
90 DAYS	BF24	3401.654	90 DAYS	BF01	4904.378
	BF54	6020.116		BF16	4223.091
0 DAY	MT21	2876.584	0 DAY	MT10	3384.909
	MT30	3638.728		MT25	3425.246
14 DAYS	MT08	3788.707	14 DAYS	MT03	3220.483
	MT20	4192.175		MT16	3876.553
28 DAYS	MT17	5650.302	28 DAYS	MT02	3122.440
	MT27	4306.405		MT45	3504.147
90 DAYS	MT22	4013.663	90 DAYS	MT15	3695.847
	MT59	3803.802		MT28	4157.659
0 DAY	BJ10	3909.448	0 DAY	BJ14	3213.476
	BJ18	4281.770		BJ28	2567.324
14 DAYS	BJ27	1772.801	14 DAYS	BJ09	3052.236
	BJ56	5144.481		BJ17	3688.276
28 DAYS	BJ07	4987.438	28 DAYS	BJ03	1080.545
	BJ11	5256.622		BJ23	3614.501
90 DAYS	BJ20	3996.645	90 DAYS	BJ04	3705.875
	BJ26	3473.614		BJ12	3617.918
0 DAY	CT17	5488.819	0 DAY	CT07	2544.780
	CT24	4237.362		CT26	2711.963
14 DAYS	CT08	4064.240	14 DAYS	CT18	2459.951
	CT12	4342.542		CT30	2808.713
28 DAYS	CT02	4187.890	28 DAYS	CT10	3001.093
	CT23	4614.898		CT25	2805.664
90 DAYS	CT04	3522.596	90 DAYS	CT09	2997.545
	CT33	4499.869		CT27	3156.599

Table B.3 -- continued

41°F UV		ENERGY (Pascal)	77°F UV		ENERGY (Pascal)
0 DAY	MA15	4688.054	0 DAY	MA23	2969.486
	MA21	4095.136		MA30	2829.140
14 DAYS	MA03	4461.416	14 DAYS	MA39	2655.028
	MA28	3284.832		MA47	3183.904
28 DAYS	MA32	4124.225	28 DAYS	MA33	3120.445
	MA35	3907.189		MA58	3312.674
90 DAYS	MA31	3695.174	90 DAYS	MA48	3853.351
	MA38	4174.704		MA50	3696.620
0 DAY	BF05	4292.911	0 DAY	BF06	3007.080
	BF17	4189.824		BF18	3612.130
14 DAYS	BF22	4366.688	14 DAYS	BF32	2928.709
	BF41	3675.335		BF44	3579.158
28 DAYS	BF33	4198.536	28 DAYS	BF48	3913.845
	BF46	3597.663		BF55	3961.236
90 DAYS	BF12	4380.696	90 DAYS	BF39	3765.859
	BF40	4178.079		BF50	3920.723
0 DAY	MT21	2876.584	0 DAY	MT10	3384.909
	MT30	3638.728		MT25	3425.246
14 DAYS	MT05	4429.702	14 DAYS	MT56	2528.047
	MT09	4470.274		MT60	2968.353
28 DAYS	MT39	4731.695	28 DAYS	MT35	3181.247
	MT57	4715.583		MT42	3076.221
90 DAYS	MT43	4549.799	90 DAYS	MT07	3558.981
	MT51	4659.072		MT47	2718.438
0 DAY	BJ10	3909.448	0 DAY	BJ14	3213.476
	BJ18	4281.770		BJ28	2567.324
14 DAYS	BJ16	5308.752	14 DAYS	BJ19	2998.753
	BJ29	4077.364		BJ36	2221.167
28 DAYS	BJ40	4230.879	28 DAYS	BJ45	3116.095
	BJ54	3618.835		BJ47	2373.666
90 DAYS	BJ31	4310.042	90 DAYS	BJ34	4144.126
	BJ50	4589.651		BJ59	3358.999
0 DAY	CT17	5488.819	0 DAY	CT07	2544.780
	CT24	4237.362		CT26	2711.963
14 DAYS	CT19	4429.465	14 DAYS	CT46	2629.368
	CT20	4105.437		CT53	2342.812
28 DAYS	CT34	4402.949	28 DAYS	CT36	2819.486
	CT47	4065.167		CT40	2732.267
90 DAYS	CT42	4372.825	90 DAYS	CT31	2486.362
	CT55	4755.087		CT38	2792.775

Table B.3 -- continued

41°F ROOF		ENERGY (Pascal)	77°F ROOF		ENERGY (Pascal)
0 DAY	MA15	4688.054	0 DAY	MA23	2969.486
	MA21	4095.136		MA30	2829.140
3 MONTH	MA44	3599.473	3 MONTH	MA34	3234.027
	MA53	3516.326		MA45	3411.778
6 MONTH	MA46	4258.846	6 MONTH	MA41	2157.806
	MA52	3959.575		MA42	3347.033
0 DAY	BF05	4292.911	0 DAY	BF06	3007.080
	BF17	4189.824		BF18	3612.130
3 MONTH	BF25	3023.948	3 MONTH	BF43	3380.581
	BF31	3474.378		BF49	4014.520
6 MONTH	BF52	4914.037	6 MONTH	BF09	3588.100
	BF60	4602.930		BF59	4176.528
0 DAY	MT21	2876.584	0 DAY	MT10	3384.909
	MT30	3638.728		MT25	3425.246
3 MONTH	MT46	2816.425	3 MONTH	MT32	3106.131
	MT50	3033.778		MT38	3302.558
6 MONTH	MT33	4908.813	6 MONTH	MT13	2393.030
	MT40	4587.419		MT31	2958.317
0 DAY	BJ10	3909.448	0 DAY	BJ14	3213.476
	BJ18	4281.770		BJ28	2567.324
3 MONTH	BJ21	2662.076	3 MONTH	BJ35	3860.301
	BJ58	2455.307		BJ52	3244.140
6 MONTH	BJ41	3973.285	6 MONTH	BJ39	2465.879
	BJ44	4355.131		BJ51	3556.385
0 DAY	CT17	5488.819	0 DAY	CT07	2544.780
	CT24	4237.362		CT26	2711.963
3 MONTH	CT32	3802.522	3 MONTH	CT45	3116.218
	CT43	4146.387		CT59	2485.282
6 MONTH	CT16	4817.742	6 MONTH	CT35	2910.825
	CT58	4911.169		CT49	2775.875

APPENDIX C

RESULTS OF SCHWEYER RHEOMETER TEST ON RECOVERED RESIDUES



2001-10-07

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DURATION		Specimen MA; 25°C				
DAYS	OVEN C	OVEN nj	FD C	FD nj	UV C	UV nj
0 DAY	0.893 0.922	8.177E+05 7.435E+05				
14 DAYS	0.730 0.937	2.181E+06 9.436E+05	0.844 0.740	1.760E+06 2.655E+06	0.918 0.836	1.575E+06 1.852E+06
28 DAYS	0.723 0.682	3.558E+06 4.218E+06	0.672 0.695	4.023E+06 3.628E+06	0.716 0.640	3.422E+06 4.751E+06
90 DAYS	0.830 0.765	3.590E+06 5.050E+06	0.860 0.842	3.068E+06 3.074E+06	0.696 0.769	4.669E+06 3.585E+06

DURATION		Specimen MA; 15°C				
DAYS	OVEN C	OVEN nj	FD C	FD nj	UV C	UV nj
0 DAY	0.812 0.635	1.990E+07 4.411E+07				
14 DAYS	0.798 0.715	3.498E+07 4.239E+07	0.564 0.547	8.169E+07 9.621E+07	0.556 0.649	8.866E+07 5.436E+07
28 DAYS	0.595 0.553	5.832E+07 7.074E+07	0.506 0.534	7.860E+07 7.478E+07	0.626 0.542	4.918E+07 7.094E+07
90 DAYS	0.547 0.619	1.072E+08 6.382E+07	0.497 0.533	1.049E+08 8.559E+07	0.552 0.612	8.003E+07 6.719E+07

DURATION		Specimen BF; 25°C				
DAYS	OVEN C	OVEN nj	FD C	FD nj	UV C	UV nj
0 DAY	0.968 0.962	9.131E+05 1.024E+05				
14 DAYS	0.911 0.831	2.182E+06 3.235E+06	0.830 0.865	2.629E+06 2.226E+06	0.809 0.957	2.614E+06 1.482E+06
28 DAYS	0.821 0.829	4.089E+06 4.220E+06	1.085 0.850	1.962E+06 4.387E+06	0.938 1.010	3.138E+06 2.153E+06
90 DAYS	0.708 0.747	1.907E+07 1.534E+07	0.683 0.764	9.879E+06 6.663E+06	0.825 0.591	1.138E+07 1.628E+07

DURATION		Specimen BF; 15°C				
DAYS	OVEN C	OVEN nj	FD C	FD nj	UV C	UV nj
0 DAY	0.617 0.707	5.384E+07 5.352E+07				
14 DAYS	0.626 0.679	7.363E+07 7.365E+07	0.741 0.542	5.700E+07 1.157E+08	0.575 0.580	8.448E+07 8.245E+07
28 DAYS	0.512 0.592	1.411E+08 1.024E+08	0.539 0.587	1.178E+08 1.102E+08	0.451 0.484	2.061E+08 1.769E+08
90 DAYS	0.437 0.488	4.738E+08 3.416E+08	0.381 0.537	3.043E+08 1.525E+08	0.628 0.501	1.413E+08 2.092E+08

DURATION		Specimen BJ; 25°C				
DAYS	OVEN C	OVEN nj	FD C	FD nj	UV C	UV nj
0 DAY	0.744 0.846	4.420E+06 2.677E+06				
14 DAYS	0.725 0.846	4.536E+06 2.490E+06	0.753 0.745	3.045E+06 3.140E+06	0.660 0.779	7.552E+06 3.962E+06
28 DAYS	0.581 0.630	1.042E+07 1.006E+07	0.670 0.654	5.841E+06 6.033E+06	0.735 0.649	4.133E+06 6.562E+06
90 DAYS	0.500 0.718	3.962E+07 1.185E+07	0.742 0.737	9.941E+06 9.410E+06	0.814 0.862	6.168E+06 4.981E+06

DURATION		Specimen BJ; 15°C				
DAYS	OVEN C	OVEN nj	FD C	FD nj	UV C	UV nj
0 DAY	0.632 0.714	6.245E+07 5.013E+07				
14 DAYS	0.587 0.591	6.235E+07 5.681E+07	0.385 0.494	1.834E+08 1.106E+08	0.447 0.535	1.592E+08 1.039E+08
28 DAYS	0.542 0.610	1.085E+08 8.295E+07	0.586 0.546	8.168E+07 8.997E+07	0.516 0.540	1.243E+08 1.115E+08
90 DAYS	0.588 0.591	1.051E+08 1.114E+08	0.481 0.514	1.951E+08 1.702E+08	0.681 0.543	8.649E+07 1.157E+08

DURATION		Specimen CT; 25°C				
DAYS	OVEN C	OVEN nj	FD C	FD nj	UV C	UV nj
0 DAY	0.813 0.772	1.533E+06 1.775E+06				
14 DAYS	0.771 0.826	2.081E+06 1.608E+06	0.582 0.721	3.479E+06 1.985E+06	0.674 0.644	3.849E+06 4.466E+06
28 DAYS	0.608 0.615	6.157E+06 5.867E+06	0.597 0.657	4.319E+06 3.545E+06	0.673 0.608	2.466E+06 3.144E+06
90 DAYS	0.556 0.651	3.026E+07 1.754E+07	0.584 0.583	8.050E+06 8.013E+06	0.767 0.635	4.120E+06 9.278E+06

DURATION		Specimen CT; 15°C				
DAYS	OVEN C	OVEN nj	FD C	FD nj	UV C	UV nj
0 DAY	0.617 0.611	5.384E+07 3.877E+07				
14 DAYS	0.512 0.558	6.886E+07 5.428E+07	0.715 0.541	4.523E+07 6.916E+07	0.484 0.570	9.242E+07 6.552E+07
28 DAYS	0.565 0.560	6.772E+07 6.800E+07	0.542 0.456	5.425E+07 8.344E+07	0.487 0.509	6.032E+07 6.737E+07
90 DAYS	0.434 0.376	3.038E+08 2.924E+08	0.437 0.569	1.290E+08 9.392E+07	0.667 0.411	6.170E+07 1.089E+08

DURATION		Specimen MT; 25°C				
DAYS	OVEN C	OVEN nj	FD C	FD nj	UV C	UV nj
0 DAY	0.906 0.877	1.296E+06 1.540E+06				
14 DAYS	0.809 0.897	2.587E+06 1.784E+06	0.817 0.847	2.146E+06 1.826E+06	0.808 0.763	2.438E+06 3.062E+06
28 DAYS	0.764 0.753	7.037E+06 7.240E+06	0.755 0.691	3.317E+06 4.577E+06	0.753 0.725	2.879E+06 3.303E+06
90 DAYS	0.602 0.736	2.341E+07 1.684E+07	0.598 0.694	1.140E+07 6.566E+06	0.811 0.796	5.444E+06 5.775E+06

DURATION		Specimen MT; 15°C				
DAYS	OVEN C	OVEN nj	FD C	FD nj	UV C	UV nj
0 DAY	0.790 0.907	2.590E+07 1.665E+07				
14 DAYS	0.555 0.541	8.331E+07 8.700E+07	0.715 0.828	4.423E+07 2.603E+07	0.459 0.509	1.406E+08 1.043E+08
28 DAYS	0.524 0.624	1.531E+08 1.060E+08	0.552 0.596	7.643E+07 7.216E+07	0.567 0.517	7.900E+07 8.684E+07
90 DAYS	0.367 0.496	5.978E+08 2.729E+08	0.428 0.538	1.954E+08 1.327E+08	0.436 0.520	2.150E+08 1.628E+08

APPENDIX D

TEST RESULTS ON THE SPECIMENS UNDER NATURAL WEATHERING

Table D.1 Indirect Tensile Test Results on the Specimens Under Natural Weathering

MONTH	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	MONTH	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)
3 MON.	MA44	2.529	5775.0	356.12	3 MON.	MA34	2.504	2812.5	175.19
	MA53	2.531	5700.0	351.31		MA45	2.525	2812.5	173.75
	AVG	2.530	5737.5	353.71		AVG	2.514	2812.5	174.47
6 MON.	MA46	2.529	6875.0	424.06	6 MON.	MA41	2.527	2100.0	129.62
	MA52	2.546	6350.0	388.96		MA42	2.521	2525.0	156.22
	AVG	2.538	6612.5	406.51		AVG	2.524	2312.5	142.92
12 MON.	MA37	2.533	6300.0	387.88	12 MON.	MA43	2.533	2700.0	166.28
	MA60	2.538	5900.0	363.73		MA51	2.530	2812.5	172.82
	AVG	2.536	6100.0	375.80		AVG	2.532	2756.3	169.55
3 MON.	BF25	2.547	6125.0	375.03	3 MON.	BF43	2.546	3225.0	197.57
	BF31	2.571	5700.0	345.75		BF49	2.555	3387.5	206.79
	AVG	2.559	5912.5	360.39		AVG	2.551	3306.3	202.18
6 MON.	BF52	2.554	7350.0	448.86	6 MON.	BF09	2.534	3362.5	206.94
	BF60	2.550	7150.0	437.28		BF59	2.555	3437.5	209.87
	AVG	2.552	7250.0	443.07		AVG	2.545	3400.0	208.41
12 MON.	BF36	2.520	6250.0	385.81	12 MON.	BF28	2.527	3550.0	219.75
	BF45	2.554	6500.0	397.21		BF38	2.552	3562.5	217.53
	AVG	2.537	6375.0	391.51		AVG	2.540	3556.3	218.64

Table D.1 -- continued

MONTH	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	MONTH	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)
3 MON.	BJ21	2.481	5100.0	320.66	3 MON.	BJ35	2.512	3312.5	205.70
	BJ58	2.523	5300.0	327.65		BJ52	2.516	3125.0	193.75
	AVG	2.502	5200.0	324.15		AVG	2.514	3218.8	199.73
6 MON.	BJ41	2.511	7200.0	447.23	6 MON.	BJ39	2.520	2487.5	153.94
	BJ44	2.513	6825.0	423.60		BJ51	2.512	3125.0	194.03
	AVG	2.512	7012.5	435.42		AVG	2.516	2806.3	173.99
12 MON.	BJ48	2.517	6375.0	395.09	12 MON.	BJ32	2.480	3300.0	207.54
	BJ49	2.530	4500.0	277.46		BJ55	2.531	3312.5	204.10
	AVG	2.523	5437.5	336.28		AVG	2.506	3306.3	205.82
MONTH	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	MONTH	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)
3 MON.	CT32	2.523	5775.0	357.06	3 MON.	CT45	2.538	2875.0	176.66
	CT43	2.529	6050.0	373.17		CT59	2.557	2762.5	168.48
	AVG	2.526	5912.5	365.12		AVG	2.548	2818.8	172.57
6 MON.	CT16	2.555	6875.0	419.69	6 MON.	CT35	2.533	2762.5	170.13
	CT58	2.561	7000.0	426.37		CT49	2.532	2750.0	169.38
	AVG	2.558	6937.5	423.03		AVG	2.533	2756.3	169.75
12 MON.	CT48	2.539	6275.0	384.87	12 MON.	CT37	2.543	2937.5	180.43
	CT57	2.552	5750.0	354.34		CT41	2.531	2962.5	181.06
	AVG	2.546	6012.5	369.61		AVG	2.537	2950.0	180.74

Table D.1 -- continued

MONTH	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)	MONTH	SPEC #	HT (inch)	LOAD (lbs)	STRESS (psi)
3 MON.	MT46	2.553	5075.0	310.05	3 MON.	MT32	2.531	2975.0	183.31
	MT50	2.548	5300.0	324.47		MT38	2.540	3012.5	184.96
	AVG	2.550	5187.5	317.26		AVG	2.536	2993.8	184.14
6 MON.	MT33	2.551	7225.0	441.75	6 MON.	MT13	2.518	2625.0	162.60
	MT40	2.534	6825.0	420.03		MT31	2.520	2912.5	180.24
	AVG	2.543	7025.0	430.89		AVG	2.519	2768.8	171.42
12 MON.	MT04	2.545	6625.0	406.02	12 MON.	MT37	2.545	3100.0	189.99
	MT41	2.545	5775.0	353.97		MT44	2.543	3200.0	196.27
	AVG	2.545	6200.0	379.99		AVG	2.544	3150.0	193.13

Table D.2 Results of Indirect Tensile Test from Previous Research

DURATION YEARS	TEMP.	SPEC #	STRESS (psi)	DURATION YEARS	TEMP.	SPEC #	STRESS (psi)	DURATION YEARS	TEMP.	SPEC #	STRESS (psi)
1	41°F	TA11	348.15	2	41°F	CH50	394.57	3	41°F	CH	363.62
1	41°F	TX06	442.54	2	41°F	B001	440.99	3	41°F	B0	386.83
1	41°F	ES44	445.63	2	41°F	MA55	286.26	3	41°F	MA	352.79
1	41°F	B016	354.34	2	41°F	AM55	448.73	3	41°F	AM	377.55
1	41°F	MA24	464.20	2	41°F	ES21	433.26	3	41°F	ES	386.83
1	41°F	AM11	464.20	2	41°F	TA53	340.41	3	41°F	TA	348.15
1	41°F	CH53	386.83	2	41°F	BE52	416.23	3	41°F	BE	379.10
1	41°F	BE44	433.26	2	41°F	TX44	471.94	3	41°F	TX	402.31

Table D.2 -- continued

DURATION			NATURAL			DURATION			NATURAL			DURATION			NATURAL		
YEARS	TEMP.		SPEC	STRESS		YEARS	TEMP.		SPEC	STRESS		YEARS	TEMP.		SPEC	STRESS	
			#	(psi)					#	(psi)					#	(psi)	
1	77°F		BE10	184.13		2	77°F		TX37	218.17		3	77°F		TX	211.21	
1	77°F		BE43	176.40		2	77°F		TX50	218.95		3	77°F		TX	214.31	
			AVG	180.27					AVG	218.56					AVG	212.76	
1	77°F		CH43	186.45		2	77°F		B011	187.23		3	77°F		B0	185.68	
1	77°F		CH49	160.92		2	77°F		B041	184.91		3	77°F		B0	201.15	
			AVG	173.69					AVG	186.07					AVG	193.42	
1	77°F		MA25	185.68		2	77°F		BE47	185.68		3	77°F		BE	189.55	
1	77°F		MA40	185.68		2	77°F		BE57	191.10		3	77°F		BE	193.42	
			AVG	185.68					AVG	188.39					AVG	191.48	
1	77°F		AM29	193.42		2	77°F		MA07	210.44		3	77°F		MA	190.32	
1	77°F		AM58	177.94		2	77°F		MA38	211.21		3	77°F		MA	201.15	
			AVG	185.68					AVG	210.83					AVG	195.74	
1	77°F		B007	174.08		2	77°F		TA30	131.52		3	77°F		TA	135.39	
1	77°F		B017	181.81		2	77°F		TA57	125.33		3	77°F		TA	137.71	
			AVG	177.94					AVG	128.43					AVG	136.55	
1	77°F		ES18	283.94		2	77°F		ES28	277.75		3	77°F		ES	301.73	
1	77°F		ES56	278.52		2	77°F		ES39	324.94		3	77°F		ES	302.50	
			AVG	281.23					AVG	301.34					AVG	302.12	
1	77°F		TA01	109.86		2	77°F		AM06	207.34		3	77°F		AM	208.89	
1	77°F		TA43	123.79		2	77°F		AM52	201.15		3	77°F		AM	217.40	
			AVG	116.82					AVG	204.25					AVG	213.15	
1	77°F		TX25	194.96		2	77°F		CH40	181.81		3	77°F		CH	177.94	
1	77°F		TX53	203.48		2	77°F		CH46	180.27		3	77°F		CH	181.04	
			AVG	199.22					AVG	181.04					AVG	179.49	

Table D.3
Results of Resilient Modulus Test on the Specimens Under Natural Weathering

41°F									
MONTH	SPEC #	HT (inch)	IR(A)	IR(B)	NATURAL		RESILIENT MODULUS		RESILIENT MODULUS TR(psi)
					TR(A)	TR(B)	IR(psi)	TR(psi)	
3 MON.	MA44	2.529	7.60	7.00	7.60	7.00	335786.14	335786.14	
	MA53	2.531	6.60	8.00	6.60	8.00	335609.22	335609.22	
	AVG	2.530	7.10	7.50	7.10	7.50	335697.68	335697.68	
6 MON.	MA46	2.529	9.70	8.00	9.70	8.00	277049.16	277049.16	
	MA52	2.546	8.70	8.00	8.70	8.00	291601.64	291601.64	
	AVG	2.538	9.20	8.00	9.20	8.00	284325.40	284325.40	
77°F									
MONTH	SPEC #	HT (inch)	IR(A)	IR(B)	NATURAL		RESILIENT MODULUS		RESILIENT MODULUS TR(psi)
					TR(A)	TR(B)	IR(psi)	TR(psi)	
3 MON.	MA34	2.504	11.10	9.30	12.00	10.20	242748.86	223066.52	
	MA45	2.525	9.00	10.50	10.00	11.00	251873.82	233882.83	
	AVG	2.514	10.05	9.90	11.00	10.60	247311.34	228474.67	
6 MON.	MA41	2.527	7.40	9.50	8.20	10.50	290355.29	262406.65	
	MA42	2.521	9.20	9.10	10.50	10.30	268780.50	236475.15	
	AVG	2.524	8.30	9.30	9.35	10.40	279567.89	249440.90	

Table D.3 -- continued

41°F

MONTH	SPEC #	HT (inch)	NATURAL			RESILIENT MODULUS	
			IR(A)	IR(B)	TR(B)	IR(psi)	TR(psi)
3 MON.	BF25	2.547	7.20	6.90	7.20	345236.57	333413.40
	BF31	2.571	8.00	8.00	8.00	301400.05	301400.05
	AVG	2.559	7.60	7.45	7.60	323318.31	317406.73
6 MON.	BF52	2.554	7.00	8.10	7.00	321531.74	321531.74
	BF60	2.550	8.10	8.00	8.10	301994.38	301994.38
	AVG	2.552	7.55	8.05	7.55	311763.06	311763.06

77°F

MONTH	SPEC #	HT (inch)	NATURAL			RESILIENT MODULUS	
			IR(A)	IR(B)	TR(B)	IR(psi)	TR(psi)
3 MON.	BF43	2.546	8.80	10.10	9.50	257692.32	238744.36
	BF49	2.555	12.10	8.20	12.90	239075.32	222625.18
	AVG	2.551	10.45	9.15	11.20	248383.82	230684.77
6 MON.	BF09	2.534	8.80	9.60	9.10	265913.34	243423.16
	BF59	2.555	9.30	8.30	10.00	275787.63	254128.91
	AVG	2.545	9.05	8.95	9.55	270850.48	248776.03

Table D.3 -- continued

41°F

MONTH	SPEC #	HT (inch)	NATURAL			RESILIENT MODULUS	
			IR(A)	IR(B)	TR(A)	IR(B)	TR(B)
3 MON.	BJ21	2.481	9.40	8.00	9.40	8.00	287279.10
	BJ58	2.523	8.50	7.60	8.50	7.60	305266.09
	AVG	2.502	8.95	7.80	8.95	7.80	296272.59
6 MON.	BJ41	2.511	7.80	8.60	7.80	8.80	301114.12
	BJ44	2.513	7.60	7.50	7.60	7.50	326777.58
	AVG	2.512	7.70	8.05	7.70	8.15	313945.85

77°F

MONTH	SPEC #	HT (inch)	NATURAL			RESILIENT MODULUS	
			IR(A)	IR(B)	TR(A)	IR(B)	TR(B)
3 MON.	BJ35	2.512	9.30	9.80	10.20	10.50	258479.63
	BJ52	2.516	7.50	9.00	8.30	9.60	298733.99
	AVG	2.514	8.40	9.40	9.25	10.05	278606.81
6 MON.	BJ39	2.520	9.60	8.80	10.20	9.60	267390.44
	BJ51	2.512	10.60	9.80	11.50	10.80	241975.77
	AVG	2.516	10.10	9.30	10.85	10.20	254683.11

238500.52

275369.32

256934.92

248484.05

221359.00

234921.52

Table D.3 -- continued

41°F

MONTH	SPEC #	HT (inch)	NATURAL			RESILIENT MODULUS	
			IR(A)	IR(B)	TR(A)	IR(B)	TR(psi)
3 MON.	CT32	2.523	7.80	7.30	7.80	7.30	325525.39
	CT43	2.529	7.50	7.20	7.50	7.20	333589.80
	AVG	2.526	7.65	7.25	7.65	7.25	329557.60
6 MON.	CT16	2.555	7.30	9.00	7.30	9.00	297744.11
	CT58	2.561	8.20	7.50	8.40	7.50	308438.79
	AVG	2.558	7.75	8.25	7.85	8.25	303091.45

77°F

MONTH	SPEC #	HT (inch)	NATURAL			RESILIENT MODULUS	
			IR(A)	IR(B)	TR(A)	IR(B)	TR(psi)
3 MON.	CT45	2.538	9.70	8.20	10.70	8.90	272910.35
	CT59	2.557	9.40	10.10	10.30	10.90	248656.45
	AVG	2.548	9.55	9.15	10.50	9.90	260783.40
6 MON.	CT35	2.533	10.40	9.30	11.40	10.20	248529.20
	CT49	2.532	9.00	10.80	10.00	11.80	247306.55
	AVG	2.533	9.70	10.05	10.70	11.00	247917.88

225642.86

Table D.3 -- continued

41°F

MONTH	SPEC #	HT (inch)	NATURAL			RESILIENT MODULUS	
			IR(A)	IR(B)	TR(A)	TR(B)	IR(psi) TR(psi)
3 MON.	MT46	2.553	6.70	7.20	6.70	7.20	349426.69 349426.69
	MT50	2.548	7.10	6.80	7.10	6.80	350158.18 350158.18
	AVG	2.550	6.90	7.00	6.90	7.00	349792.43 349792.43
6 MON.	MT33	2.551	7.60	8.00	7.60	8.00	311592.24 311592.24
	MT40	2.534	8.00	8.20	8.00	8.20	302025.03 302025.03
	AVG	2.543	7.80	8.10	7.80	8.10	306808.63 306808.63

77°F

MONTH	SPEC #	HT (inch)	NATURAL			RESILIENT MODULUS	
			IR(A)	IR(B)	TR(A)	TR(B)	IR(psi) TR(psi)
3 MON.	MT32	2.531	9.30	9.20	10.20	9.40	264789.41 249928.78
	MT38	2.540	9.00	9.80	9.90	10.70	259640.91 236953.84
	AVG	2.536	9.15	9.50	10.05	10.05	262215.16 243441.31
6 MON.	MT13	2.518	9.50	8.50	10.50	9.40	273585.74 247464.49
	MT31	2.520	8.60	6.80	9.10	7.80	319479.49 291123.32
	AVG	2.519	9.05	7.65	9.80	8.60	296532.61 269293.90

Table D.4 Results of Resilient Modulus Test from Previous Research

41°F											
DURATION		RESILIENT MODULUS		RESILIENT MODULUS		DURATION		RESILIENT MODULUS		RESILIENT MODULUS	
YEAR	SPEC #	IR(psi)	TR(psi)	YEAR	SPEC #	IR(psi)	TR(psi)	YEARS	SPEC #	IR(psi)	TR(psi)
1	TA11	258980.79	258980.79	2	CH50	286083.43	286083.43	2	CH50	286083.43	286083.43
1	TX06	309473.89	309473.89	2	B001	296423.79	296423.79	2	B001	296423.79	296423.79
1	ES44	307539.68	307539.68	2	MA55	300038.71	300038.71	2	MA55	300038.71	300038.71
1	B016	271858.28	271858.28	2	AM55	265980.27	265980.27	2	AM55	265980.27	265980.27
1	MA24	341710.76	341710.76	2	ES21	315425.32	315425.32	2	ES21	315425.32	315425.32
1	AM11	270364.56	270364.56	2	TA53	315425.32	315425.32	2	TA53	315425.32	315425.32
1	CH53	298220.30	298220.30	2	BE52	276440.16	276440.16	2	BE52	276440.16	276440.16
1	BE44	289449.11	289449.11	2	TX44	300038.71	300038.71	2	TX44	300038.71	300038.71

Table D.4 -- continued

77°F

DURATION YEAR	SPEC #	RESILIENT MODULUS		DURATION YEARS	SPEC #	RESILIENT MODULUS		RESILIENT MODULUS TR(psi)
		IR(psi)	TR(psi)			IR(psi)	TR(psi)	
1	BE10	292894.94	257624.86	2	TX37	279581.53	257624.86	
1	BE43	236568.99	218694.89	2	TX50	281179.14	267425.81	
	AVG	264731.96	238159.88		AVG	280380.33	262525.34	
1	CH43	258980.79	235437.08	2	B011	248516.92	223665.22	
1	CH49	225717.20	202495.26	2	B044	252340.25	233205.45	
	AVG	242348.99	218966.17		AVG	250428.58	228435.34	
1	MA25	252340.25	226757.37	2	BE47	271858.28	246031.75	
1	MA40	281179.14	251052.80	2	BE57	264550.26	241207.59	
	AVG	266759.70	238905.09		AVG	268204.27	243619.67	
1	AM29	256283.07	223665.22	2	MA07	237711.83	221650.22	
1	AM58	246031.75	214874.89	2	MA38	291161.83	264550.26	
	AVG	251157.41	219270.06		AVG	264436.83	243100.24	
1	B007	246031.75	216768.06	2	TA30	234315.95	209388.72	
1	B017	252340.25	228866.74	2	TA57	231015.72	201665.37	
	AVG	249186.00	222817.40		AVG	232665.84	205527.04	

Table D.4 -- continued

77°F

DURATION		SPEC #	RESILIENT MODULUS		DURATION YEARS	SPEC #	RESILIENT MODULUS		RESILIENT MODULUS TR(psi)
YEAR			IR(psi)	TR(psi)			IR(psi)	TR(psi)	
1	ES18		289449.11	282795.11	2	ES28	291161.83	291161.83	
1	ES56		268887.15	264550.26	2	ES39	291161.83	281179.14	
	AVG		279168.13	273672.69		AVG	291161.83	286170.48	
1	TA01		213940.65	185684.34	2	AM06	276440.16	251052.80	
1	TA43		251052.80	221650.22	2	AM52	246031.75	227807.17	
	AVG		232496.73	203667.28		AVG	261235.96	239429.99	
1	TX25		267425.81	253640.98	2	CH40	220656.27	201665.37	
1	TX53		305629.50	276440.16	2	CH46	261735.90	232105.42	
	AVG		286527.65	265040.57		AVG	241196.09	216885.39	

Table D.5
Results of Fracture Energy on the Specimens Under Natural Weathering

41°F ROOF	ENERGY (Pascal)	77°F ROOF	ENERGY (Pascal)
0 DAY	MA15 4688.05 MA21 4095.14 MA44 3599.47	0 DAY	MA23 2969.49 MA30 2829.14 MA34 3234.03
3 MONTH	MA53 3516.33 MA46 4258.85	3 MONTH	MA45 3411.78 MA41 2157.81
6 MONTH	MA52 3959.58 MA43 3471.70	6 MONTH	MA42 3347.03 MA37 3325.04
12 MONTH	MA51 2766.11	12 MONTH	MA60 3816.82
0 DAY	BF05 4292.91 BF17 4189.82 BF25 3023.95	0 DAY	BF06 3007.08 BF18 3612.13 BF43 3380.58
3 MONTH	BF31 3474.38 BF52 4914.04	3 MONTH	BF49 4014.52 BF09 3588.10
6 MONTH	BF60 4602.93 BF28 4061.21	6 MONTH	BF59 4176.53 BF36 2835.59
12 MONTH	BF38 3834.65	12 MONTH	BF45 3870.37
0 DAY	MT21 2876.58 MT30 3638.73 MT46 2816.43	0 DAY	MT10 3384.91 MT25 3425.25 MT32 3106.13
3 MONTH	MT50 3033.78 MT33 4908.81	3 MONTH	MT38 3302.56 MT13 2393.03
6 MONTH	MT40 4587.42 MT04 2830.86	6 MONTH	MT31 2958.32 MT37 3352.34
12 MONTH	MT41 2357.41	12 MONTH	MT44 3329.32

Table D.5 -- continued

41°F ROOF	ENERGY (Pascal)	77°F ROOF	ENERGY (Pascal)
0 DAY	BJ10 3909.45	0 DAY	BJ14 3213.48
	BJ18 4281.77		BJ28 2567.32
3 MONTH	BJ21 2662.08	3 MONTH	BJ35 3860.30
	BJ58 2455.31		BJ52 3244.14
6 MONTH	BJ41 3973.29	6 MONTH	BJ39 2465.88
	BJ44 4355.13		BJ51 3556.39
12 MONTH	BJ48 3976.17	12 MONTH	BJ32 3385.73
	BJ49 3351.30		BJ55 3197.26
0 DAY	CT17 5488.82	0 DAY	CT07 2544.78
	CT24 4237.36		CT26 2711.96
3 MONTH	CT32 3802.52	3 MONTH	CT45 3116.22
	CT43 4146.39		CT59 2485.28
6 MONTH	CT16 4817.74	6 MONTH	CT35 2910.83
	CT58 4911.17		CT49 2775.88
12 MONTH	CT37 2650.70	12 MONTH	CT48 3072.10
	CT41 3175.08		CT57 2800.70

Table D.6
Results of Fracture Energy on the Specimens Under Natural Weathering
(from Previous Research)

TEMP.	DURATION YEAR	SPEC#	ENERGY (Pascal)	TEMP.	DURATION YEAR	SPEC#	ENERGY (Pascal)	TEMP.	DURATION YEAR	SPEC#	ENERGY (Pascal)
41°F	1 YEAR	TA11	5175.46	41°F	2 YEAR	TA53	5072.53	41°F	3 YEAR	TA	2883.50
41°F	1 YEAR	TX06	4478.98	41°F	2 YEAR	TX44	4879.56	41°F	3 YEAR	TX	1726.99
41°F	1 YEAR	ES44	3874.15	41°F	2 YEAR	ES21	4329.61	41°F	3 YEAR	ES	2834.25
41°F	1 YEAR	BO16	2906.58	41°F	2 YEAR	BO01	4755.96	41°F	3 YEAR	BO	3272.27
41°F	1 YEAR	MA24	5333.95	41°F	2 YEAR	MA55	2852.64	41°F	3 YEAR	MA	4123.49
41°F	1 YEAR	AM11	4443.28	41°F	2 YEAR	AM55	4741.73	41°F	3 YEAR	AM	2012.83
41°F	1 YEAR	CH53	3920.04	41°F	2 YEAR	CH50	3471.82	41°F	3 YEAR	CH	551.69
41°F	1 YEAR	BE44	5271.41	41°F	2 YEAR	BE52	4941.02	41°F	3 YEAR	BE	1560.58

Table D.6 -- continued

TEMP.	DURATION YEAR	SPEC#	ENERGY (Pascal)	TEMP.	DURATION YEAR	SPEC#	ENERGY (Pascal)	TEMP.	DURATION YEAR	SPEC#	ENERGY (Pascal)
77°F	1 YEAR	TA01	2019.14	77°F	2 YEAR	TA30	2269.68	77°F	3 YEAR	TA1	2508.55
77°F	1 YEAR	TA43	2136.96	77°F	2 YEAR	TA57	2541.16	77°F	3 YEAR	TA2	2208.15
77°F	1 YEAR	TX25	3570.06	77°F	2 YEAR	TX37	4305.12	77°F	3 YEAR	TX1	3371.44
77°F	1 YEAR	TX53	4341.76	77°F	2 YEAR	TX50	3888.10	77°F	3 YEAR	TX2	3818.05
77°F	1 YEAR	ES18	4523.87	77°F	2 YEAR	ES28	4555.40	77°F	3 YEAR	ES1	3432.10
77°F	1 YEAR	ES56	4558.15	77°F	2 YEAR	ES39	5751.91	77°F	3 YEAR	ES2	4517.63
77°F	1 YEAR	B007	3402.51	77°F	2 YEAR	B011	3096.67	77°F	3 YEAR	B01	3006.02
77°F	1 YEAR	B017	3381.44	77°F	2 YEAR	B041	3582.20	77°F	3 YEAR	B02	3358.56
77°F	1 YEAR	MA25	4476.23	77°F	2 YEAR	MA07	4705.37	77°F	3 YEAR	MA1	3553.55
77°F	1 YEAR	MA40	3952.32	77°F	2 YEAR	MA38	4424.76	77°F	3 YEAR	MA2	4090.41
77°F	1 YEAR	AM29	4269.29	77°F	2 YEAR	AM06	3968.96	77°F	3 YEAR	AM12	4419.06
77°F	1 YEAR	AM58	4284.46	77°F	2 YEAR	AM52	4181.80	77°F	3 YEAR	AM16	3811.95
77°F	1 YEAR	CH43	3323.60	77°F	2 YEAR	CH40	3451.22	77°F	3 YEAR	CH1	3036.69
77°F	1 YEAR	CH49	3340.98	77°F	2 YEAR	CH46	2915.31	77°F	3 YEAR	CH2	3101.04
77°F	1 YEAR	BE10	3350.17	77°F	2 YEAR	BE47	3022.13	77°F	3 YEAR	BE38	3346.89
77°F	1 YEAR	BE43	3298.78	77°F	2 YEAR	BE57	3392.85	77°F	3 YEAR	BE40	2980.33

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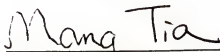
BIOGRAPHICAL SKETCH

Jih-Min Shiau was born on April 17, 1959, in Taichung County, Taiwan, R.O.C.. He received his Bachelor of Science degree in civil engineering from the National Central University, Taiwan, in 1981. After graduation, he was employed as an assistant engineer in the Bureau of Public Roads, Taiwan. During the employment, his responsibilities included pavement design, bridge design, construction site supervision and surveying.

He resigned in June, 1984, to enroll in the graduate program of civil engineering at the University of Florida. Under the supervision of Dr. Frank C. Townsend, he received his Master of Engineering degree with specialization in geotechnical engineering, in 1986. Then he joined the Ph.D. program and worked under the supervision of Dr. Mang Tia. He expects to finish his Ph.D. study in December, 1990.

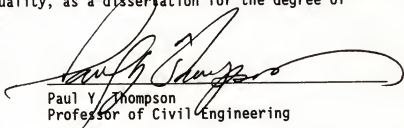
Jih-Min Shiau is married to Mei-Jung Tsao, who received a Specialist Degree from College of Education, University of Florida. They have a lovely daughter, Connie Jayhern Shiau, who was born on December 24, 1989.

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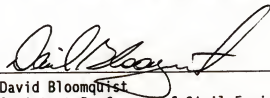
Mang Tia, Chairman
Associate Professor of Civil Engineering

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Paul Y. Thompson
Professor of Civil Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.



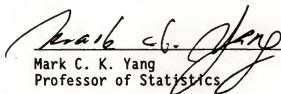
David Bloomquist
Assistant Professor of Civil Engineering

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Gale C. Page
Bituminous Materials and Research Engineer
Florida Department of Transportation

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.


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Professor of Statistics

This dissertation was submitted to the Graduate Faculty of the College of Engineering and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

December 1990


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